

DEVELOPMENT AND IMPLEMENTATION OF A MECHANISTIC AND EMPIRICAL PAVEMENT DESIGN GUIDE (MEPDG) FOR RIGID PAVEMENTS

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1.0 INTRODUCTION

This document is the annual report for the third year of Phase I of ODOT project 2208 “Development and Implementation of a Mechanistic and Empirical Pavement Design Guide (MEPDG) for Rigid Pavements”. The focus of this project is on assisting ODOT in implementing the MEPDG into their rigid pavement design practices. It was decided to best accomplish this goal by completing the following tasks:

- A. Review of the inputs to the MEPDG and determine the sensitivity on the final design values.
- B. Investigate base material practices for concrete pavements through a literature review and survey of experiences from others.
- C. Increase the quantity of weather sites in Oklahoma that provide environmental inputs for the MEPDG.
- D. Examine different curing methods for rigid pavement construction and their impact on the early age curling and warping of continuous reinforced concrete pavements
- E. Provide regional material input parameters that can be used in the MEPDG for the design of rigid pavements

In the first year of the project task A and C was completed and outlined in the first annual report. In the second annual report Task B was completed. This report contains the details for Task D and E.

A complete summary report for Phase I is planned to be submitted that outlines the findings from all of the tasks.

2.0 IMPACT ON CURING TO REDUCE CURLING IN CONCRETE

Currently, the MEPDG requires that the user input the curing methodology to be used in a pavement's construction. From investigations on this project it appears that this is a major parameter in the design of continuous reinforced concrete pavement (CRCP). The wet mat cure has been indicated by the MEPDG to be the most effective curing technique; however, it is also the least economical to be implemented in the field.

Classically the primary reason that curing is required in concrete is to promote hydration, which in turn decreases the permeability and increases the strength of the surface concrete. One challenging aspect to this task is that there is not a standard method of investigating the effectiveness of different curing techniques.

In concrete pavements curing can have a number of interesting impacts on the curling of a concrete pavement. These include differential shrinkage of the concrete at the surface compared to the concrete at depth. Also, differential temperatures during set of the concrete can lead to a built in curl to a concrete pavement that may increase stresses and lead to premature cracking. Much new information was learned from this work that has allowed wet curing to be directly compared to the use of curing compounds. This data provides new insights into the curling and warping of concrete pavement and the long term performance.

2.1 THE IMPACT OF WET AND SEALED CURING TECHNIQUES ON CURLING FROM DRYING SHRINKAGE

2.1.1 INTRODUCTION

The purpose of curing is to maintain adequate moisture content and temperature in concrete for a period of time immediately after placing and finishing in order to develop the desired properties. Proper curing can increase durability, strength, water-tightness, abrasion resistance, volume stability, and resistance to freezing and thawing and deicers; therefore, the exposed slab surfaces are significantly sensitive to curing. The improvement in concrete properties is rapid at early ages but continues more slowly thereafter for an indefinite period (Kosmatka, Kerkhoff, Panarese 2003).

Wet curing methods maintain the presence of mixing water and saturation in the concrete during early ages. Wet curing methods include ponding, fogging, and saturated wet coverings. These methods afford some cooling through evaporation, which can be beneficial in hot weather. Fabric coverings saturated with water, such as burlap, cotton mats, rugs and etc. are commonly used for wet curing.

The early age period in the life of concrete is approximately the first seven days after final set. Concrete properties change rapidly at early ages. Change in properties continues more slowly thereafter. Rapid and large moisture loss from the surface of a slab can reduce the degree of hydration. Also, harmful consequences like plastic shrinkage cracking, and decreases in strength, durability, and abrasion resistance can

occur without precautionary curing. Some amount of curling is expected on every pavement project (ACI 302.1R). For the large moisture loss at the top layers, the difference in moisture content results in more drying shrinkage at the top than the bottom causing the slab to curl upward at the edges as shown in Figure 1 (Ytterberg 1987, Parts I, II, III). If the concrete is restrained, either internally or externally, restraint may cause the concrete to crack due to drying shrinkage.

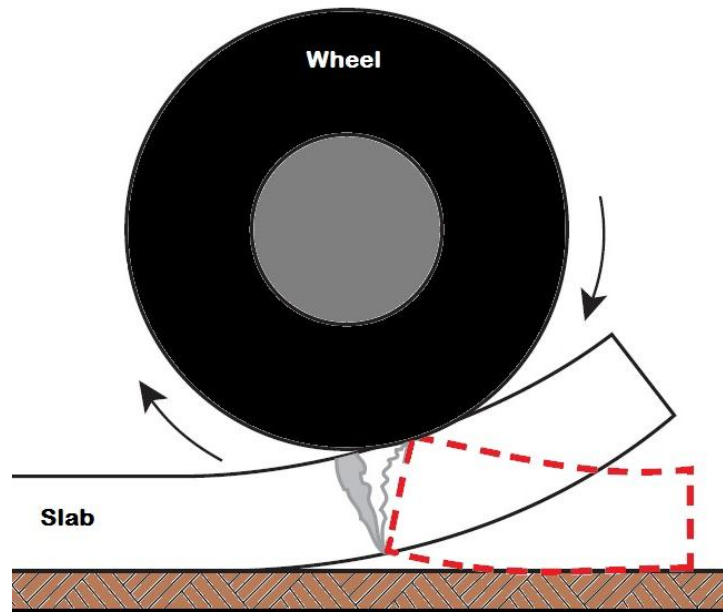


Figure 1: Warped Slab Cracks Under The Heavy Wheel Loading (Kosmatka et al 2003)

The amount and type of curing can affect the rate and ultimate amount of drying shrinkage. Wet curing methods, such as fogging or wet burlap, hold off shrinkage until curing is terminated, after which it has been reported that concrete dries and shrinks at a normal rate (Kosmatka et al 2003). The slab starts drying and shrinking immediately after the termination of the curing if the concrete has been kept continuously moist since casting and finishing. The moisture distribution in a hardened slab is assumed to be uniform before drying begins (Hanson 1968) and it starts changing as concrete loses moisture (Hedenblad 1997). Depending on the length of the drying period, drying conditions, and the initial water content, the RH at equilibrium varies (Hedenblad 1997). To avoid or lessen this moisture gradient, the top and the bottom of the slabs should be uniformly kept moist or dry. For points deeper within the concrete the drying time will increase to reach to a certain RH (Monfore 1963), and curing for longer than one day will significantly add to the drying time (Hedenblad 1997).

The drying shrinkage of the cement paste is six to eight times greater than amount observed in concrete (Bisschop 2002). The paste shrinks about 1.7 times more than mortar (Holt 2002). The shrinkage can be decreased by reducing the paste content, adding aggregate content (Tazawa et al. 1995). The impact of fly ash was found to either

have no impact or increase the shrinkage of a mixture (Setter and Roy 1978; Justnes et al, 1998). Air content less than 8% was found to not influence shrinkage (Davis and Troxell 1954). So the shrinkage of the concrete (S_c) is highly affected by the shrinkage of the cement paste (S_p) and aggregate volumetric fraction (g) because the aggregate restrains the shrinkage of the cement paste in the concrete (Pickett 1956):

$$\text{Equation 1: } S_c = S_p(1 - g)^n$$

The capillary forces during drying are generally the reason for shrinkage (Lane, Scott, and Weyers 1997). The drying shrinkage in cement paste is caused by a negative pressure called capillary tension (P_{cap}) inside the liquid phase after formation of menisci (curved liquid-vapor interfaces); so shrinkage of paste (S_p) can be defined as a function of capillary tension (P_{cap}), degree of saturation of cement paste (S), bulk modulus of paste (K), and modulus of solid skeleton inside cement paste (K_s) (Mackenzie 1950; Bentz et al. 1998):

$$\text{Equation 2: } S_p = \frac{s}{3} P_{cap} \left(\frac{1}{K} - \frac{1}{K_s} \right)$$

Due to the generation of the hydration products in the cement matrix, autogenous shrinkage occurs; this component may be more important for concrete mixtures with w/c less than 0.40 (Tazawa 1999). The autogenous shrinkage will increase by reducing the w/cm and increasing the cement fineness since the capillary tension mechanism will cause higher tension in the pore water of the finer structure (Bentz et al. 2001a, Jensen and Hansen 1996). Also, due to the smaller volume of the hydration products than that of the reactants, there is an approximately 8% to 9% reduction in volume after hydration reactions called chemical shrinkage (Jensen and Hansen 2001). Due to lack of water, concrete sealed against moisture loss with w/c < 0.5 cannot progress to its complete potential hydration (Powers, 1948). Concrete with w/c < 0.4 can dry itself from inside (Powers 1948; Mills 1966; Cather 1994; Meeks and Carino 1999). Due to low permeability at those low w/c ratios, the curing water does not infiltrate away from the surface (Cather 1994; Meeks and Carino 1999). This layer of the concrete is highly affected by the curing water (Cather, 1992), which continues to a depth of approximately 1/4" to 3/4" depending on the concrete characteristics (Carrier 1983; Spears 1983). The lower permeability of the concrete causes the slower moisture movement between the cured surface and the interior (Pihlajavaara 1964, 1965).

The formation of the menisci occurs in external drying as well; the specimen suffers from both external drying at the exposed surface and internal drying (self-desiccation) in an unsealed specimen. The radius of these menisci is reduced as moisture evaporates, and the internal RH of the cement paste decreases until the internal RH reaches the ambient RH, or equilibrium (Radlinska et al. 2008). The formation of the menisci and generation of the capillary tension (P_{cap}) can be related, according to the Laplace equation, if γ is surface tension of pore fluid, θ is the liquid-solid contact angle, and r is the radius of the curvature of the meniscus (Adamson and Gast 1997):

$$\text{Equation 3: } P_{cap} = -\frac{2\gamma \cos(\theta)}{r}$$

The solid surfaces or pore walls will be pulled together by this negative pressure, causing the volume change or shrinkage. The capillary tension is also related to the RH of the cement paste by the Kelvin equation (Adamson and Gast 1997):

$$\text{Equation 4: } P_{cap} = \frac{RT \ln(RH)}{V_m}$$

Where R is the universal gas constant, T is the temperature and RH is the internal relative humidity, and V_m is the molar volume of pore solution.

Others have suggested that the drying shrinkage may be increased by curing longer than 4 to 8 days and less than 35 to 50 days (Perenchio 1997). The shorter curing time will result in a faster drying rate (Hedenblad 1997; Jackson and Kellerman 1939). Wet curing for 28 days was found to increase the time needed to reach a certain RH by approximately 1 month (Hedenblad 1997). S suggested by ACI committee 302 slabs should not be cured by adding water like wet burlap and should be protected from any external water if drying time is critical (ACI 302.2R-06).

It has been shown that the drying shrinkage and curling may get worse when a vapor barrier is used immediately under the concrete. This causes the slab to lose little or no water from the bottom, while the top dries and shrinks at a faster rate (Anderson and Roper 1977, Nicholson 1981, Turenne 1978). Installing an impervious membrane like vapor/moisture barrier below the slab makes maintaining the moisture at the top of the slab highly essential to minimize curling. Therefore, ACI 302.1R suggests placing a 4 in. drainable, compressed fill on top of the vapor barriers to minimize this moisture gradient and to consequently decrease the curling. Also, for avoiding or minimizing this problem after curing, the wet burlap should be replaced with a plastic sheet until the concrete surface has become dry under the sheets (ACI 308R-01). Using a sheeting material to cure for 3 days is recommended for floor slabs (Suprenant and Malisch 1999c). Installing a floor covering causes the moisture movement from the bottom to the top of the slab; this movement will reduce the curling initially due to the expansion at the top as the moisture content there increases and the shrinkage at the bottom as the moisture content there decreases (Tarr et al. 2006).

While it is common to recommend that concrete receive a prolonged wet cure, some previous literature suggests that this may promote drying shrinkage. In a concrete pavement one concern is differential drying shrinkage that would occur over the cross section. This would cause curling and possibly cause damage to the pavement because of loss of support. Currently in the literature there is almost no work that has been done to investigate the impact of sustained wet curing on curling. This research will use paste and concrete specimens to further explore these concepts.

2.1.2 EXPERIMENTAL INVESTIGATIONS

2.1.2.1 Paste Beams

2.1.2.1.1 Materials

The Portland cement used in these tests was a type I/II, according to ASTM C 150, and its oxide analysis per ASTM C 114 and the phases' concentrations are shown in the following Table 1. The paste mixtures in this experiment had a water to cement ratio (w/c) of 0.34, 0.42, and 0.5.

**Table 1: Oxide Analysis Of The Cement Used For Paste Beams
And The Phase Concentrations**

Chemical Test Results	
SiO ₂	20.23
Al ₂ O ₃	4.77
Fe ₂ O ₃	3.23
CaO	64.15
Phase concentrations	
C ₃ S	70.69
C ₂ S	4.68
C ₃ A	7.18
C ₄ AF	9.83

2.1.2.1.2 Sample Preparation And Methods

The paste mixtures were prepared according to ASTM C 305. Three paste beams with dimensions of 39.4" x 2.4" x 0.5" were prepared in plastic molds from each mixture. After casting all specimens were cured with wet burlap for 24 hours. To restrict the moisture loss to a single surface the sides and bottom face of the beam were sealed with melted wax after demolding. Testing was also done with aluminum tape to compare the results. Little difference was found in the specimens and so the wax was used for all subsequent testing. The finished surface of the beam was exposed to different curing techniques for different durations. An overview of these specimens is shown in Figure 2. Thinner concrete members were chosen as they shrink faster than the thick members due to the faster drying rate; the shrinkage rate is generally assumed to be related to the ratio of the specimen's volume to its surface area (Hansen and Mattock 1966). The shape of the specimen determines the distance for water movement to the dry surface and the internal strains caused by the non-uniform shrinkage; the developed stresses and

shrinkage strains due to the moisture gradients during drying is highly related to the specimen size (McDonald and Roper 1993; Pickett 1946; Browne 1967).

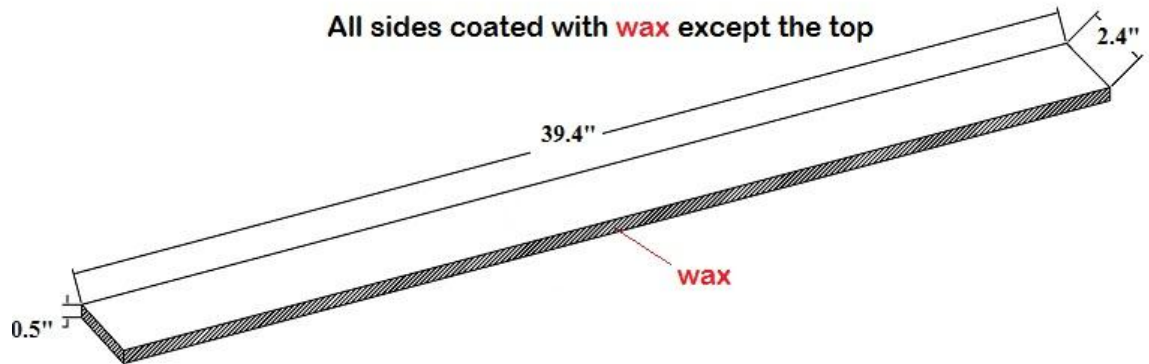


Figure 2: A Waxed Paste Beam On All Sides Except The Finished Surface

The specimens were demolded, weighed, sealed with wax, and reweighed. Finally these specimens were stored in an environmental chamber at 73°F and 40% relative humidity. This caused a moisture gradient to form in the beam over time due to the water loss from only one side.

In this experiment since the top of the surface was not sealed with wax and water was allowed to evaporate. This differential loss of moisture caused a shrinkage gradient in the specimen. This gradient caused differential strain to occur and results in the curling of the specimen. This test is advantageous, as the moisture loss is quick and the resulting gradients can be quite large. This leads to a significant deformation of the specimens that is easy to measure. To ensure that the curling measurements were only the result of this differential in strain caused by the drying, the beams were stored on their sides. This test is similar to previous work done by Burke (2004) to investigate the effectiveness of shrinkage reducing admixtures.

2.1.2.1.3 Test Procedure And Measurement

To measure the curling, two ends of the specimen are attached to a flat aluminum plate with the uncoated surface facing the plate, as shown in Figure 3. The distance between the aluminum plate and the specimen is measured at regular locations along the length with a caliper that reads to 0.0005". The curling of the beam is symmetric and the maximum is at the middle of the beam. The weight of the sample is also measured at different times with a scale accurate to 0.1 grams. This measurement was used to get information about the moisture content of the specimen.

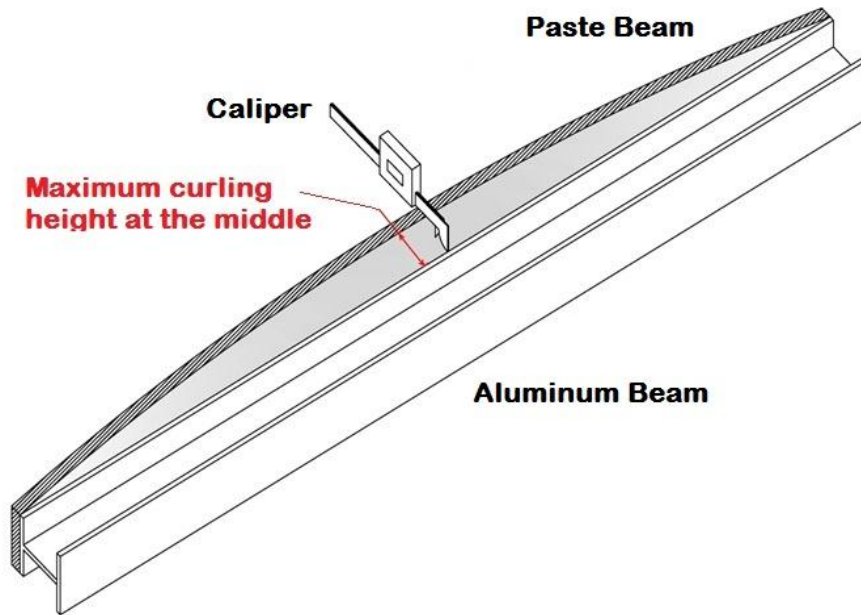


Figure 3: Measuring The Curling Height Using A Caliper

The focus of this work was to compare the performances of different durations of wet and sealed curing. All samples were wet cured at 73°F for 1 day before demolding. This was necessary to ensure the specimens gained enough strength. Some samples were also kept in wet burlap for 1, 3, 7, and 14 days of additional curing after demolding and waxing. The curing was then removed, and the specimens were subjected to the 40% relative humidity and 73 °F drying environment. In addition to wet curing, several specimens were cured in a sealed plastic bag for 1 and 3 days. This curing was similar to the wet burlap cure, but no external moisture was added to the specimens during the sealed curing process. Other samples received no curing after demolding.

2.1.2.2 Concrete Beams

2.1.2.2.1 Materials

The cement used in this test is type I, according to ASTM C 150, and its chemical analysis is per ASTM C 114 shown in the following Table 2 beside the phases' concentrations.

**Table 2: Chemical Analysis Of The Cement Used In This Project
For Concrete Beams**

Chemical Test Results	
SiO ₂	21.13
Al ₂ O ₃	4.71
Fe ₂ O ₃	2.55
CaO	62.06
Phase concentrations	
C ₃ S	52.14
C ₂ S	20.22
C ₃ A	7.69
C ₄ AF	7.96

Samples were made with dolomitic limestone aggregate and natural river sand. An ASTM C 618 class C fly ash was also used. A wood rosin AEA was used for the first and second beams with no curing and 3 days wet curing techniques, but not for any others. During the testing it was found that it was too difficult to produce consistent air content between mixtures, and so the AEA was no longer used. The concrete beams were sealed in a similar manner to the paste beams. A moisture barrier was used as a form liner. This material had a plastic water-proof membrane on one side and fibers on the other. The fibers were oriented so that they bonded to the wet concrete and provided a tight fit of the water proof layer on the outside of the beam. The interface between the beam and the water membrane was sealed with hot glue to insure a good bond was

2.1.2.2.2 Mixture Proportions And Procedures

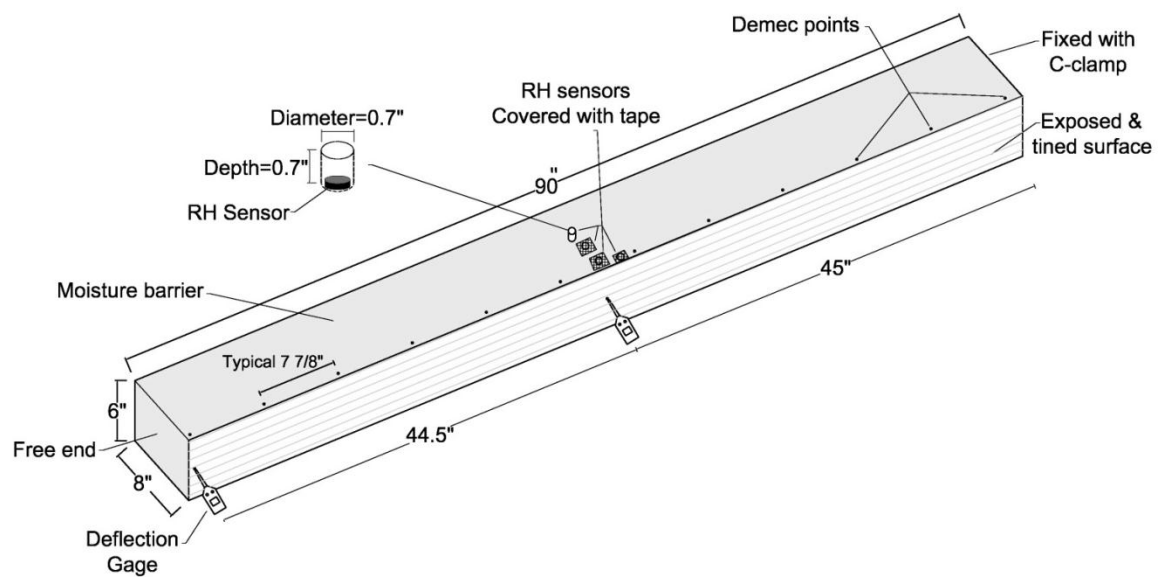
In this experiment we used water to cement ratio equal to 0.41 for concrete beams. All of the aggregate, both coarse and fine, were charged into the mixer along with approximately two-thirds of the mixing water. The combination was mixed for three minutes. Next any clumped fine aggregate was removed from the walls of the mixer. Then the cement was loaded into the mixer, followed by the remaining mixing water. The mixer was turned on for an additional three minutes. Once this mixing period was complete, the mixture was left to “rest” for the following two minutes while the buildup of material along the walls was removed. Next the mixer was started and the admixtures were added and the mixer was allowed to run for the remainder of the three minutes. The slump (ASTM C 143), unit weight (ASTM C 138) and the air content (ASTM C 231) were measured. The typical mix proportion used in this test is presented in Table 3 for on a cubic yard basis.

Table 3: Mix Proportion Used In This Experiment Per Cubic Yard

Cement (lb)	451.2
Fly Ash (lb)	112.8
Course aggregate (lb)	1842.1
Fine aggregate (lb)	1276.1
Water (lb)	207.1

2.1.2.2.3 Sample Preparations, Casting And Curing

In this experiment the size of the concrete specimen investigated was 7.5'×6"×8". All sides of the beam were sealed with a synthetic moisture barrier except the top surface for each specimen. An overview of this specimen is shown in Figure 4. This specimen is similar to work done by Hansen et al. (2007) and Springersmidt et al (2001), with some modifications.

**Figure 4: Concrete Beam Dimension And Details**

After placing and vibrating the concrete in 3 different layers the top surface was screeded with a piece of wood; burlap was dragged over it, and finally it was tined with a steel comb, creating tines with transverse grooves 1/16" wide, 1/4" deep, and with center to center spacing of 1". The sample was carefully demolded 5 hours after casting. Then it was sealed at the seams with wax. Specimens were prepared with no curing and 1 and 3 days of wet cure with wet burlap and a plastic tarp. The beams were flipped on their side and placed on wooden dowels after the curing was completed. This was done to minimize the influence of gravity on the results. After placing the beam on its side, it

was fixed at the end with a C-clamp, steel plates, and rubber bearing pads in an environmental chamber at 73° F temperature and 40% relative humidity.

2.1.2.2.4 Test Procedure And Measurement

The relative humidity was measured at 0.5", 1", 3", and 5" from the finished surface by using the DS1923 Hygrochron Temperature/Humidity Logger iButtons. The sensors were placed in 0.7" deep holes with 0.7" diameter that were cast into the side of the concrete beam as shown in Figure 5. During demolding the forms used to make these holes were removed and the holes were sealed with water proof tape. Five days after the beam was stored on its side relative humidity gages were inserted into the beam. These sensors were programmed to take relative humidity measurements every hour. This wait period was used so that the gages did not fail due to the high amount of moisture in the beam. The holes were again sealed with water proof tape after the gages were added. This tape was removed briefly when data was obtained from the sensors.



Figure 5: Plan View Of The Test Setup Showing The Holes Covered By Tape, Deflection Gauge Secured To The Beam, And Demec Points Glued On The Surface Of The Concrete

The curling height of the beam was measured at two different locations: 45" and 89.5" from the end that is clamped. The accuracy of this gage was 0.0005". Also the surface strain of the beam was measured at 10 different locations, as shown in Figure 4 and Figure 5. Surface mounted stainless steel gage points were glued to the surface of the concrete beam. This was achieved by burning through the membrane in a localized area and then gluing one of these gage points. A mechanical strain gage was used to measure the movement of machined cones in points over time. The accuracy of this gage was 4 microstrain. These measurements were taken to check the curling measurements of the beam.

2.1.2.2.5 Calibration Of RH Sensors

The iButton sensors were calibrated according to ASTM E 104 “Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions” with four different salt saturated solutions. The relative humidity calibration range was between 57.6% and 97.3%. This was chosen in order to cover the ranges of humidity expected in the testing. A specific calibration was generated for each iButton.

2.1.3 RESULTS

2.1.3.1 Paste Beams

A typical result for a paste beam is shown in Figure 6. This figure shows the typical curves gained by measuring the deflection of the beam at different locations over time for a sample that was not cured after demolding with a 0.5 w/c. The maximum curling is at the middle of the specimen.

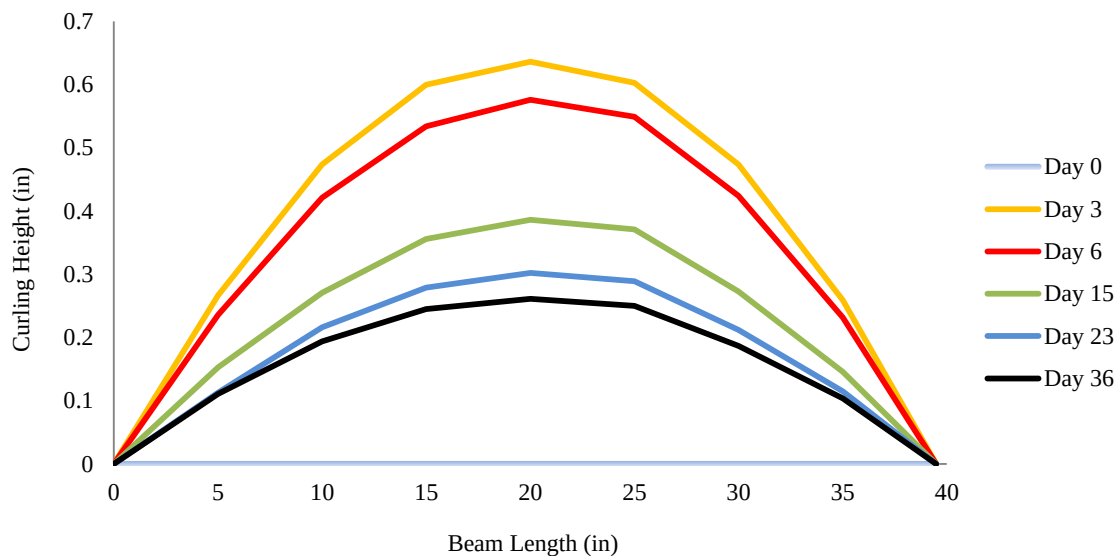


Figure 6: Curling Height Of A No-Cured Paste Beam Mixed With W/C=0.5

The following Figure 7 shows the change of the beam’s weight after being exposed to the drying environment.

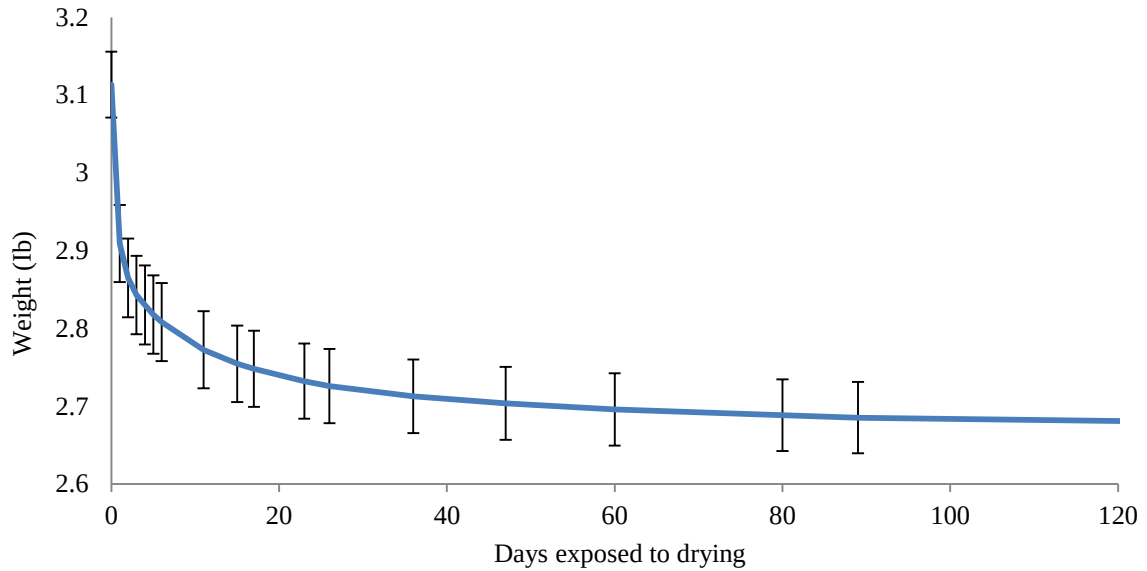


Figure 7: No-Cured Paste Beam's Weight vs. Age

The moisture loss and the maximum curling height of samples of $w/c=0.42$ cured with wet burlap for additional 1, 3, 7, and 14 days and the measurements for a no-cured specimen over the time periods are shown in Figure 8 and Figure 9 respectively. The red markers show the point of maximum curling. Note that the time to this point increases with more curing. This was consistent for all of the specimens.

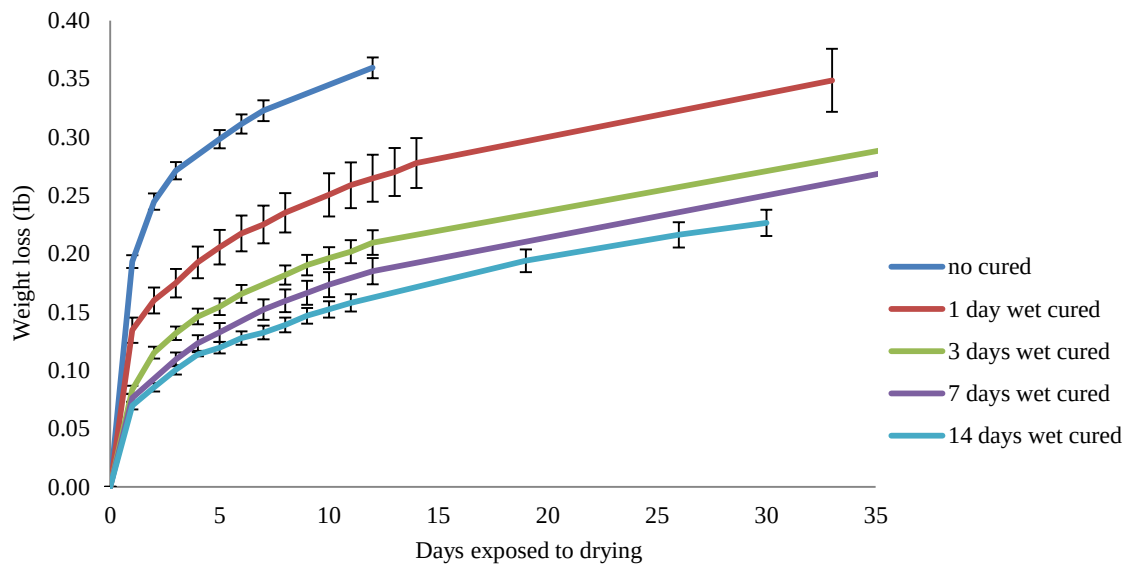


Figure 8: Weight Loss vs. The Age Of The Paste Specimen

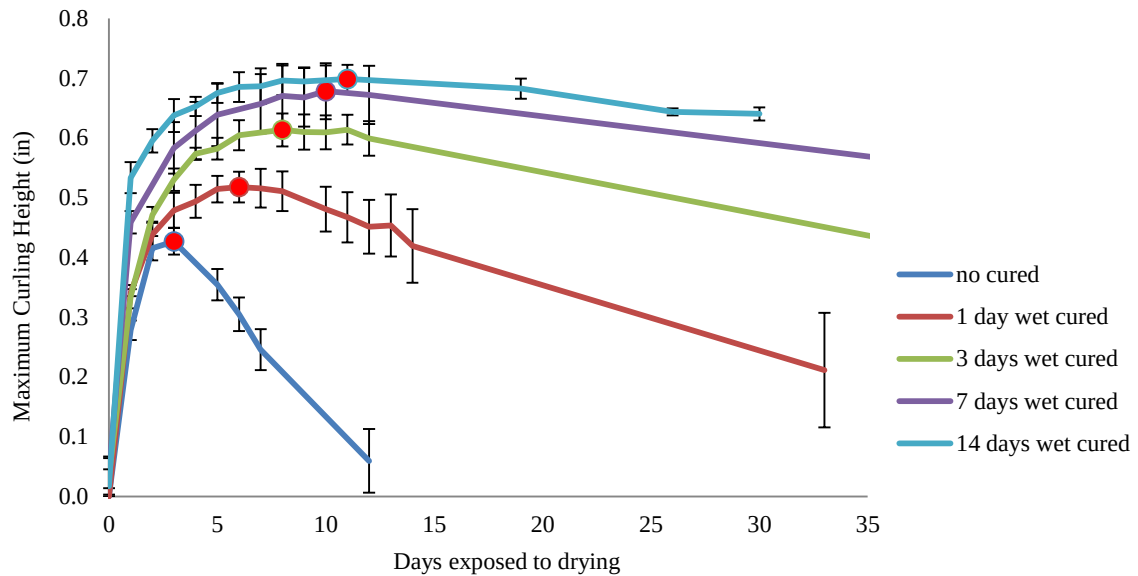


Figure 9: Paste Beam's Maximum Curling Height vs. Time

The moisture loss and the maximum curling height of samples with the same $w/c=0.42$ sealed with a plastic bag for 1 and 3 days and the measurements for a no cured specimen at the same ages are shown in Figure 10 and Figure 11 compared to specimens of 1 and 3 days of additional wet curing.

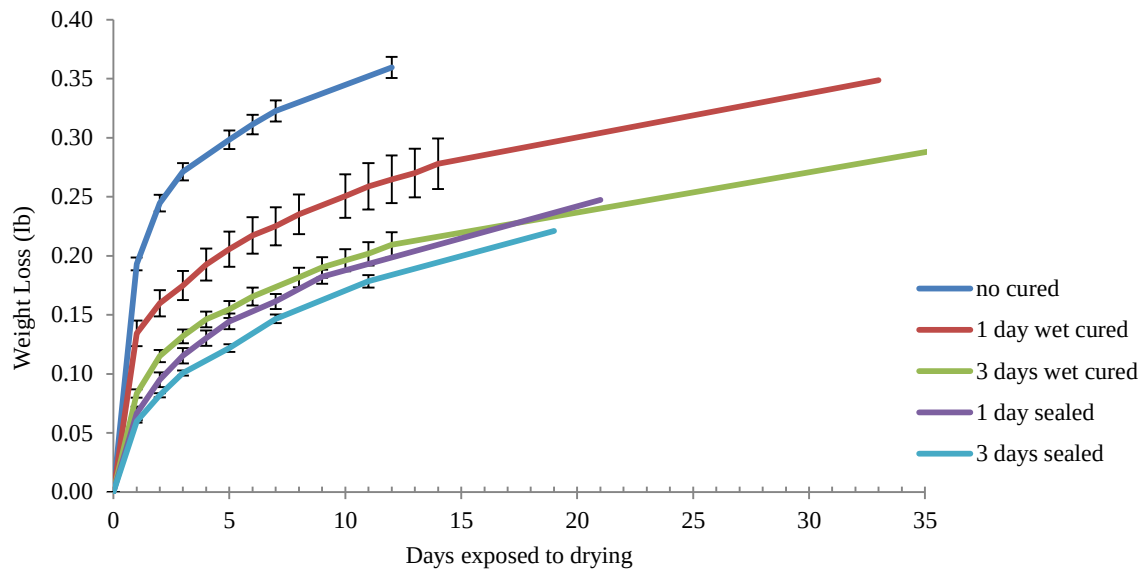


Figure 10: Weight Loss vs. Age Of The Paste Specimen

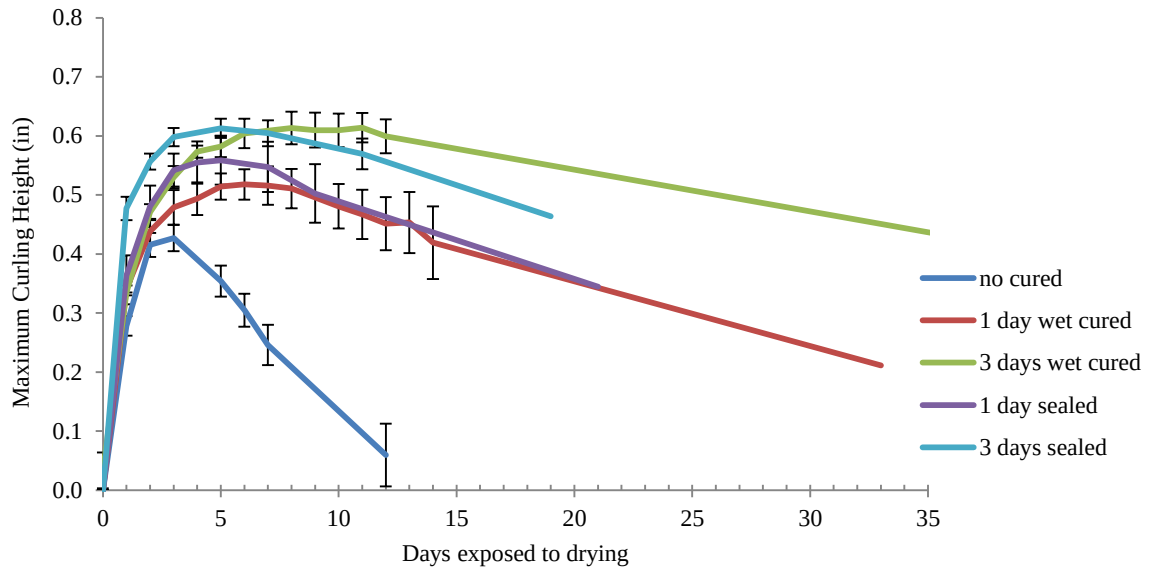


Figure 11: Paste Beam's Maximum Curling Height vs. Days Exposed to Drying

Figure 12 summarizes the response of the samples with different w/c and curing period.

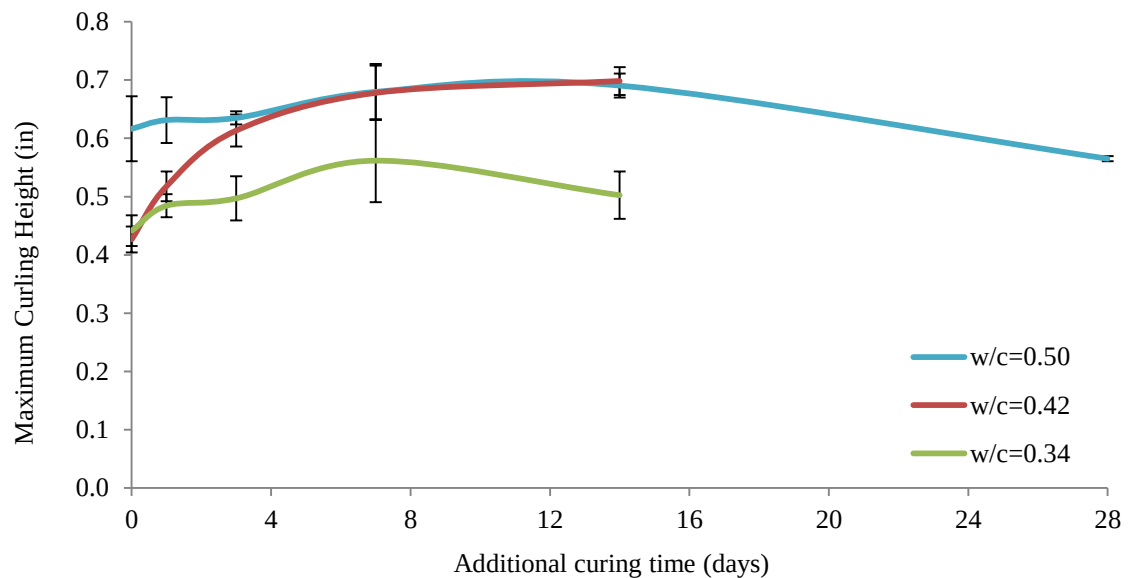


Figure 12: Comparison Between The Maximum Deflections Of Paste Beams With Different W/C Ratios

Figure 13 presents the weight loss of the specimens at maximum deflection versus curing time.

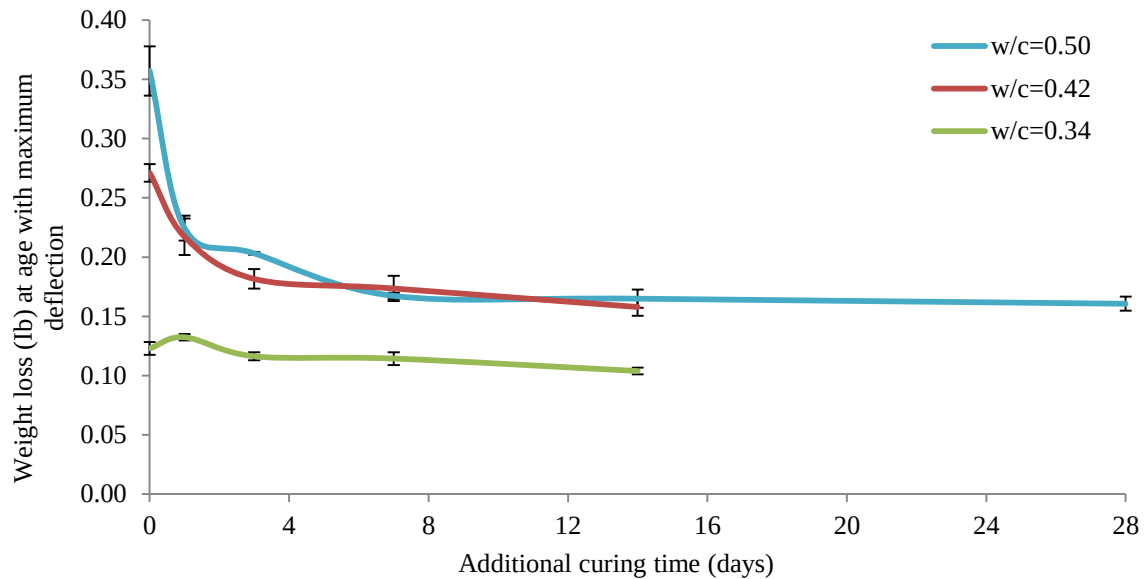


Figure 13: Weight Losses Of Paste Beams With Different W/C Ratios At Age With Maximum Curling Height

Figure 14 presents the weight loss after 11 days versus the additional curing time.

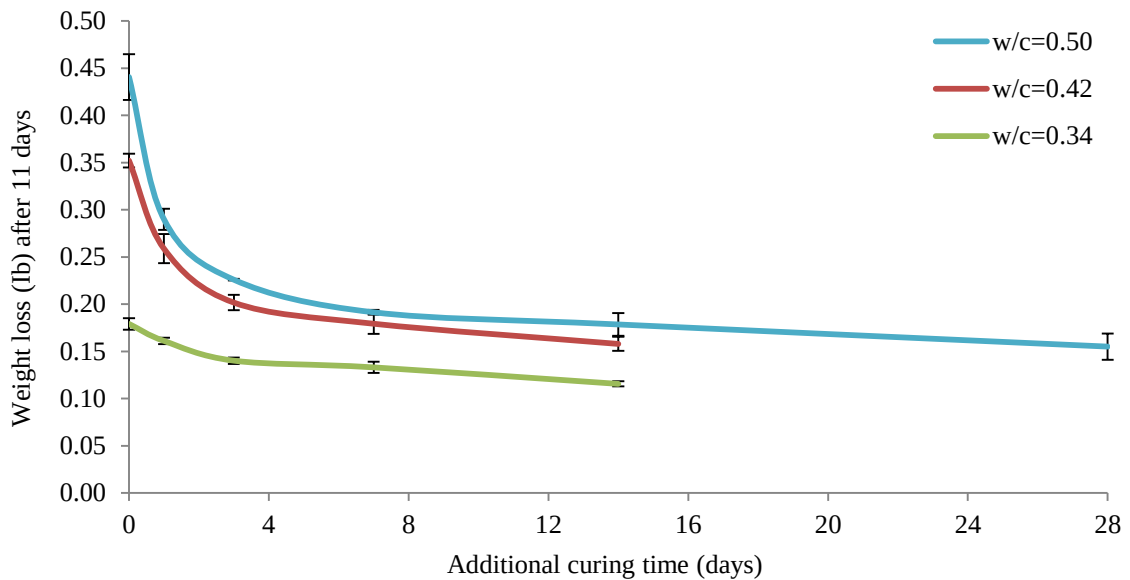


Figure 14: Weight Losses Of Paste Beams With Different W/C Ratios After 11 Days

2.1.3.2 Concrete Beams

The average surface strain over the length of the beam and the tip deflection during the drying period are shown in Figures 15 and 16 for the specimens investigated. The methods used in this experiment are no-curing, 1-day wet curing, and 3-day wet curing.

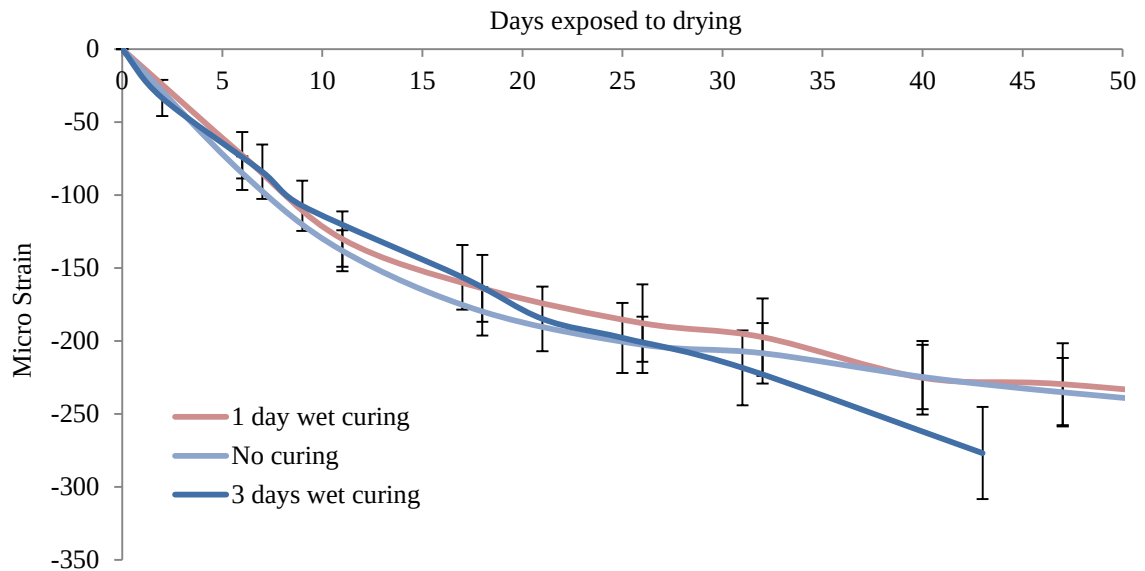


Figure 15: Average Surface Strain vs. Concrete Beam's Length With Age

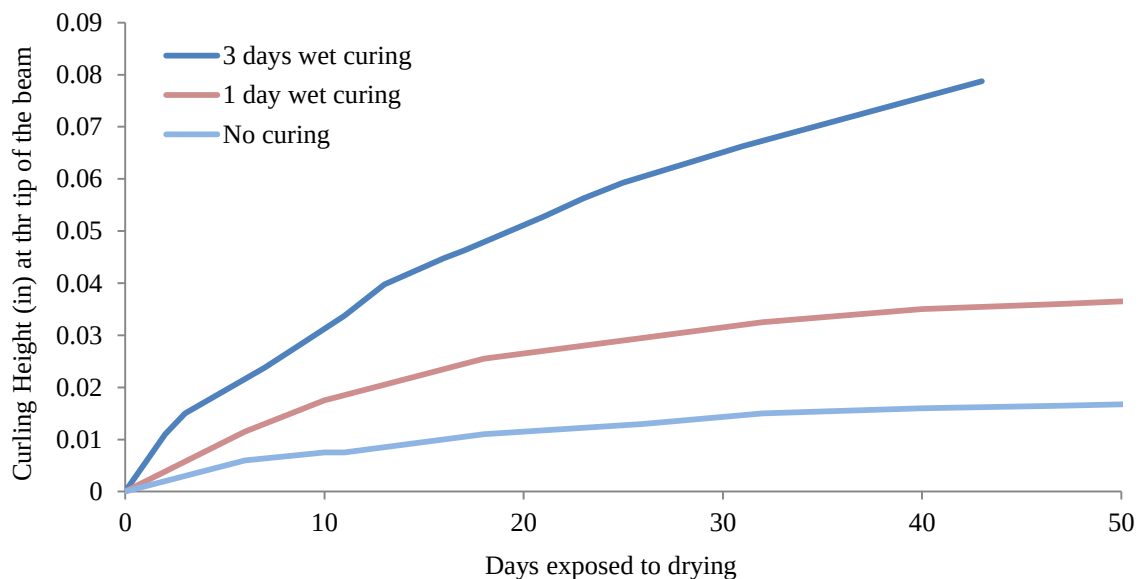


Figure 16: The Tip Deflection For The Specimens Investigated

A typical plot of the relative humidity versus the days of drying is shown for a beam that was not cured is shown in Figure 17 for different depths.

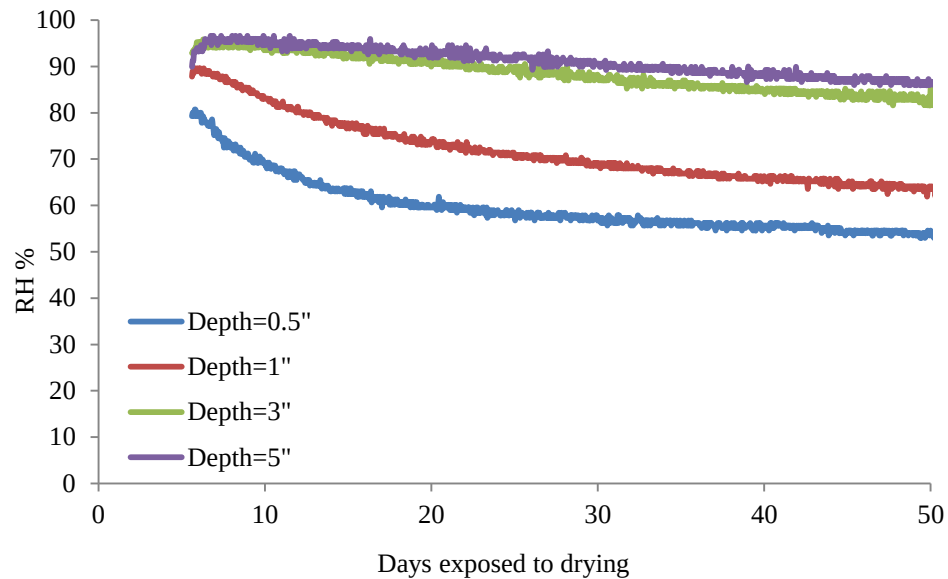


Figure 17: The Relative Humidity Of The No Curing Technique In Different Depths vs. Age For Concrete Beams

The relative humidity profiles for no-curing at 6, 15, 25 and 50 days after exposure are all shown in Figure 18.

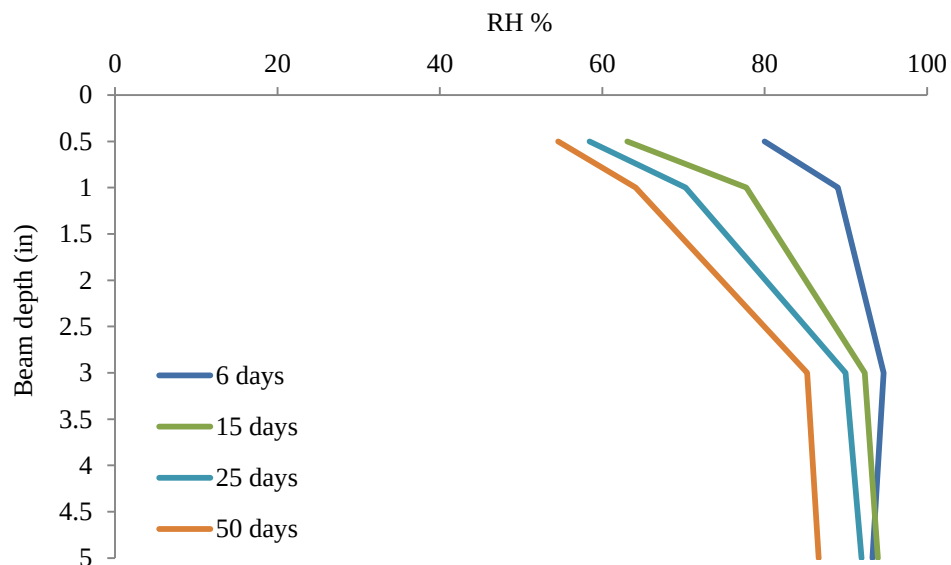


Figure 18: The RH Profiles For No Curing At 6, 15, 25 And 50 Days After Exposure For Concrete Beams

The relative humidity profiles for 1 day wet curing at 6, 15, 25, and 50 days are shown in Figure 19.

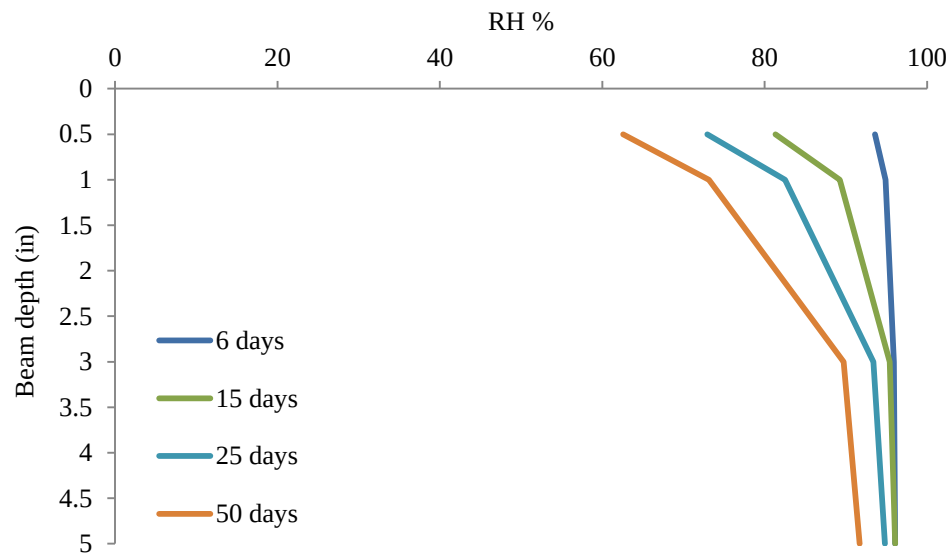


Figure 19: The RH Profiles For 1 Day Wet Curing At 6, 15, 25 And 50 Days After Exposure For Concrete Beams

The relative humidity profiles for 3 days wet curing at 8, 15, 25, and 50 days after exposure are all shown in Figure 20.

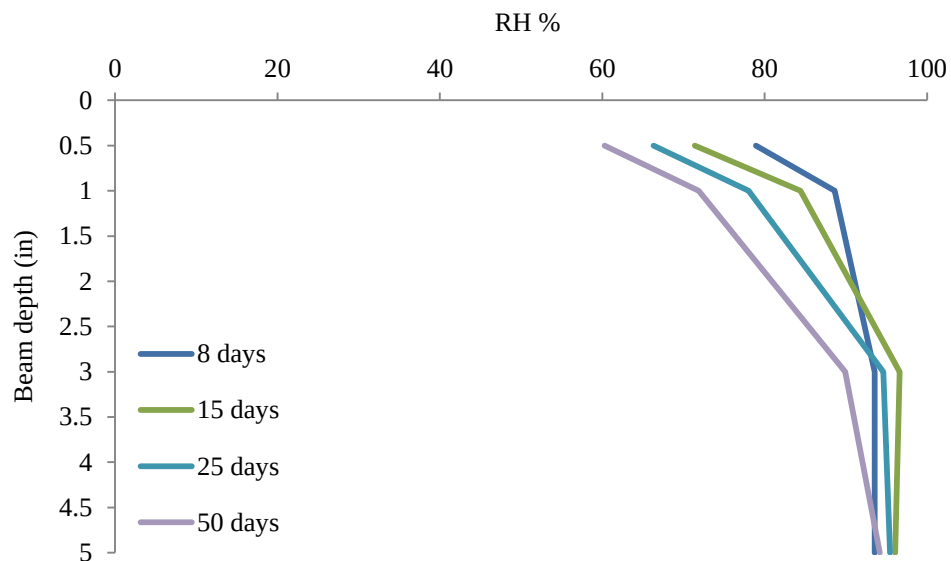


Figure 20: The RH Profiles For 3 Days Wet Curing At 8, 15, 25 And 50 Days After Exposure For Concrete Beams

The following Figure 21 shows the comparison between the RH profiles of the considered techniques after 50 days.

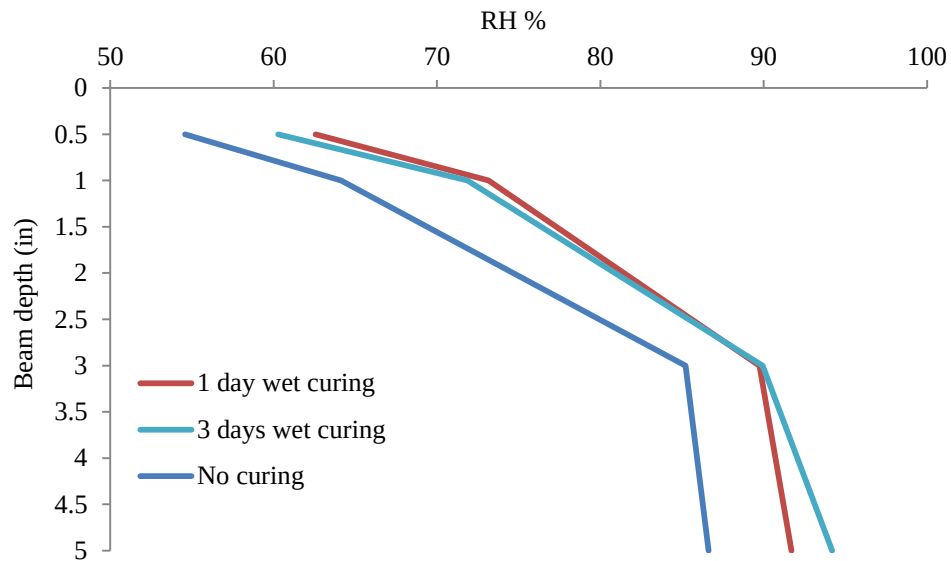


Figure 21: The RH Profiles After 50 Days For Different Methods For Concrete Beams

Figure 22 shows the integrated area under the RH profiles over the age for the wet curing and no curing methods. This graph is an indication of the total moisture loss for the sample.

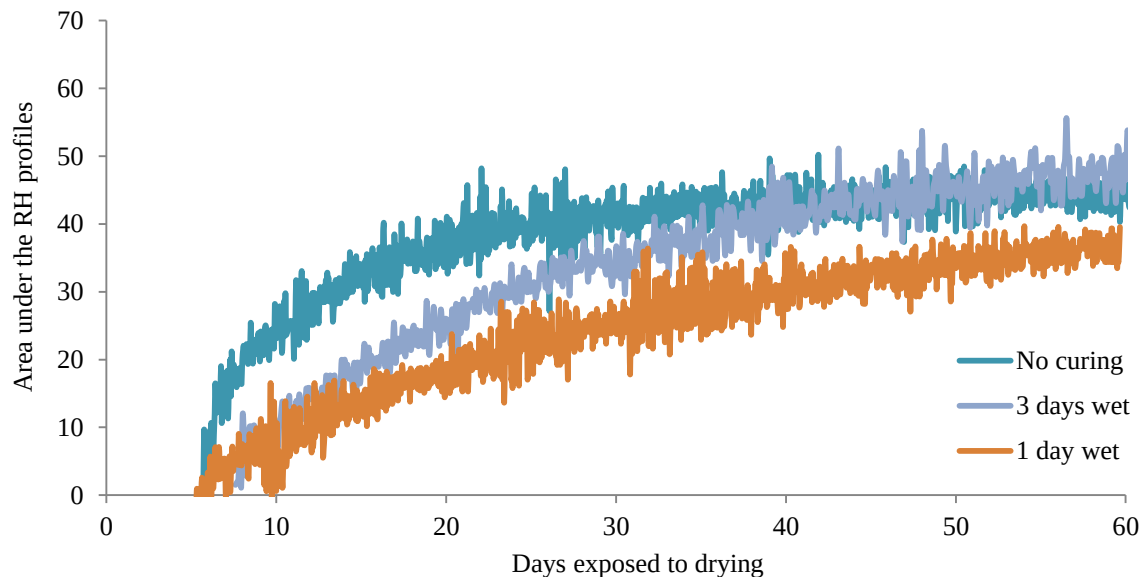


Figure 22: Integrated Area Under The RH Profiles (Depth x RH) Over The Age For Concrete Beams

2.1.4 DISCUSSION

2.1.4.1 Paste Beams

With this technique the maximum deflection was always found to be at the middle of the beam. This is to be expected since the beam was not restrained and is assumed to lose water uniformly over its surface. This means that there should be a consistent moisture gradient throughout the entire specimen. As is observed in Figure 16, the paste beam starts to deflect downwards. This is because the moisture gradient in the beam decreases with increased drying. This water loss would be expected until the internal RH of the beam reaches equilibrium with the surroundings.

Figure 8 shows that the specimens that did not receive curing lost moisture faster than the specimens that had received some amount of wet curing. This result suggests that there is a decreased porosity in the specimens that received the extended curing. In Figure 9 it can be seen that the wet curing lead to a greater degree of maximum deflection on drying. It can also be seen that this point of maximum curling occurred after a later number of drying days with prolonged curing times. Again this data suggests that the prolonged wet curing refined the pore structure of the paste.

It is likely that when the moisture is lost in the small capillaries that this will cause a greater amount of shrinkage in the cement paste. This statement is supported by equation 3. As the radius of the pore decreases the pressure produced should increase by an inverse relationship.

Others have noticed similar observations. Hedenblad (1997) suggested that with prolonged wet curing that the top surface will have fine capillary pores due to the longer hydration process. Moreover, additional curing may increase the water content of the thin paste bars, which will increase the drying time. Findings are in conflict to work by Supernant (2002) who claims that curing primarily impacts when concrete will start to curl and not the magnitude of curling. Others have also suggested that extended curing only delays curling; it does not reduce curling (ACI 360R-2006).

The results in Figure 10 show that when the beam is cured by sealing it in a plastic sheet that the beam lost moisture more slowly than wet curing. Figure 11 shows that the maximum deflection was very similar between the wet curing and the sealed specimens for the same duration of curing. Again, it was witnessed that the longer the material was cured, the more curling occurred.

Specimens that are cured by not supplying extra water but sealing them seem to have a similar performance as the wet curing techniques. They seem to promote hydration and the production of small pore size distribution. One difference between the specimens is that the sealed cure seems to lose less moisture than the wet cured samples. This suggests that additional water is added to the wet cured samples during the curing process. However, this additional water does not seem to largely impact the amount of curling that occurs. This observation is in line with the current mechanisms for drying shrinkage that suggest water loss at the walls of a capillary are the primary cause of

drying shrinkage and not losses in the bulk. By adding more bulk water to the paste then this does not impact the water at the capillary walls.

Figure 12 shows that the additional wet curing seems to increase the maximum curling of the paste for curing up until 14 days and then ultimately decrease the curling for longer curing. This can be seen that the curling for mixtures with a 0.50 w/c start to decrease after 28 days of wet curing and after 14 days for 0.34 w/c. A specimen was not investigated for a 0.42 w/c but this would be expected to be between these values. The reason for this behavior is not clear. Other researchers have reported similar observations in concrete. Work by Perenchio relating the period of moist curing and drying shrinkage for concrete with various w/c, showed that periods of curing greater than 4 to 8 days and less than 35 to 50 days may increase the drying shrinkage (ACI 209.1R-2005).

Considering the specimens with no additional curing in Figure 12, the maximum deflection of the sample with 0.42 w/c has a similar performance to 0.34 w/c for a low amount of curing and then increases to be very similar to a 0.50 w/c after 7 days of curing.

Past researchers have shown that as the w/c increases so does the drying shrinkage (U.S. Bureau of Reclamation 1975; Schmitt and Darwin 1999; Darwin et al. 2004). In general, samples of higher w/c ratios have more construction water and, due to less fine pores at the surface, they start drying earlier, which will increase the drying rate (Hardenblad 1997). It is not clear why the 0.42 w/c specimen showed similar performance to the 0.50 w/c after 7 days of curing.

Figure 13 and 14 summarize the weight loss of the specimens for different w/c ratios at the maximum curling deflections (before curling down) and at 11 days. Both graphs show less moisture loss with an extended curing period. The reason, as explained earlier for Figure 12, is due to the finer pores at the surface of the sample after the wet curing which delay the external drying and reduce the drying rate (Hedenblad 1997).

2.1.4.2 Concrete Beams

The surface strain and tip deflection results after about 40 days in Figures 15 and 16 show that there does not seem to be much difference in performance with no curing and 1 day. However increased curling was observed for 3 days of wet curing. After about 20 days, the curling deflection of the 3 day wet cure specimen is higher than that of the 1 day wet curing method, and it demonstrates the maximum deflection amongst all techniques after 40 days. This is similar to the data found with the paste beams.

Others, Lyse (1935), Carlson (1938), Keene (1961), and California Department of Transportation (1963), have reported that the duration of moist curing of concrete does not have much effect on ability of a structure to resist drying shrinkage. More work may be needed to look at curing periods longer than 3 days in the concrete testing. It may be possible that the improvements in tensile strength created by wet curing are offset by the increases in drying shrinkage.

Because the shrinkage of the concrete is caused by the shrinkage of the paste as shown in Equation 1 (Pickett 1956); therefore it is expected that similar results would be observed in concrete and paste. In both systems it appears that samples that have finer capillary pores from curing would have a higher capillary tension as expressed in Equation 2 and 3 (Mackenzie 1950; Adamson and Gast 1997; Bentz et al.1998).

Figure 17 shows that the relative humidity of the top surface at 0.5" from the exposed side changes faster than the measurements at the bottom of the beam. This is expected as the surface of the beam is exposed to a much greater degree of drying.

Figures 18, 19, and 20 show the RH profiles for no curing, 1-day, and 3-day wet curing. They present that the no curing has a faster decrease in relative humidity over the depth after exposure, while the 1-day and 3-day wet curing methods have slower moisture loss over time. Figure 21 compares the RH profiles of the abovementioned methods after 50 days; the no-curing methods has less humidity at and near the top surface while the RH values near the bottom layers are very close together for no-curing and wet curing methods.

Figure 22 shows the integrated area under the RH profiles for the aforementioned methods. The graph for no-curing technique is above those for the wet curing techniques at the early ages, but they meet each other at later ages.

These graphs for no curing technique validate the reason for having the faster weight losses due to the higher porosity concrete. The graphs for wet curing techniques keep increasing, showing their continuous water losses, their slower drying rates, and their delay in reaching the maximum curling deflections which could be expected in later ages, as seen in Figure 15.

2.1.5 CONCLUSIONS

In this chapter wet curing methods were compared to sealed and no-curing methods; it was found that wet curing on the exposed surface of a sealed beam decreases the rate of weight loss from drying but increases ultimate curling deflection. This data suggests that extended wet curing would be expected to cause an increase in the amount of curling that occurs in a slab on grade. Similar observations have been observed for drying shrinkage in concrete beams but never applied to increases in curling. Due to the wet curing process, the surface of the beam has a finer pore-structure (Hedenblad 1997) and consequently a higher negative pressure or capillary tension upon drying (Mackenzie 1950; Adamson and Gast 1997; Bentz et al.1998). This increase in capillary tension has been suggested to be the primary mechanism for drying shrinkage (Lane, Scott, and Weyers 1997).

In all of the tests presented a one dimensional drying front was used through use of impermeable boundaries. Nicholson (1981) showed that serious shrinkage curling due to an increase in moisture gradient can occur when concrete slabs are cast on an impervious

base. Because curling and drying shrinkage are both a function of potentially free water in the concrete at the time of concrete set, curing methods that retain water in the concrete will delay shrinkage and curling of enclosed slabs-on-ground. If the drying front occurs from the top and bottom of the concrete then the curling would be reduced because of the decrease in the gradient.

2.2 IMPACT ON CURING COMPOUNDS TO REDUCE CURLING IN CONCRETE FROM DRYING SHRINKAGE

2.2.1 INTRODUCTION

This chapter reviews the effectiveness of curing compounds to resist curling from differential drying by comparing one of the common curing techniques to wet curing methods.

Liquid membrane-forming compounds consist of waxes, resins, chlorinated rubber, and other materials that reduce evaporation of moisture from concrete. They are the most widely used method for curing not only freshly placed concrete, but also for extending the curing of concrete after the removal of forms or after early wet curing (Kosmatka et al 2003).

According to ACI 308R-01 curing compounds have several advantages:

1. *They do not need to be kept wet to ensure that they do not absorb moisture from the concrete;*
2. *They are easier to handle than burlap, sand, straw or hay; and*
3. *They can often be applied earlier than water-curing methods (immediately after finishing without the need to wait for final setting of the concrete).*

Liquid membrane-forming compounds for curing concrete meet the requirements of ASTM C 309 include:

- Type 1, clear;
- Type 1D, clear with fugitive dye;
- Type 2, white pigmented;
- Class A, unrestricted compositions or wax-based products; and
- Class B, resin-based compositions

Loss of some moisture from the surface of concrete cured with these compounds is allowable; depending on the application and ambient conditions in the field, these compounds have a variable potential for water retention (Mather 1987, 1990; Shariat and Pant 1984; Senbetta 1988). The amount and type of curing can affect the rate and ultimate amount of drying shrinkage. Curing compounds, sealers, and coatings can trap free moisture in the concrete for long periods of time, resulting in delayed shrinkage (Kosmatka et al 2003).

The curing compounds should be agitated or stirred before use and applied uniformly at the recommended rate. Since a textured surface has a larger surface area than a flat surface then more coverage would be expected. Some have reported that a tined surface has at least twice the area of a floated surface and verification of coverage rate is more difficult for deeply textured surfaces. It has been recommended that curing compounds should be applied in two applications to ensure uniform and more complete coverage (Shariat and Pant 1984). They can be applied by hand or power sprayer with proper

nozzles in the pressure range of 25 to 100 psi. Also, they should be applied immediately after the surface water disappears or after the final finishing of the concrete. A delay in application could cause the concrete surface to dry and the compound might absorb into the concrete, which would deter the formation of the desired membrane (ACI 308R-01). On the other hand, applying the curing compound on freshly cast concrete might result in map cracking; the disappearance of surface water will be stopped temporarily, but bleeding might continue. The bleed water will reduce the capability of the compound to maintain the moisture content of the concrete. White-pigmented compounds help guarantee uniform coverage and are considered to reflect light. A typical application of a curing compound is shown in Figure 23.



Figure 23: The Power-Driven Spray To Perform A Uniform Application On A Tinned Surface (Ye et al, TxDOT 2009)

The application rate of the curing compound should be determined based on surface texture and application device in order to obtain uniform coverage. The five factors listed below affect the curing compound application (Minnesota DOT 1999; Texas DOT 2009; Iowa DOT 2002):

- nozzle type: spray pattern, droplet size, pump pressure, spray angle, flow rate
- nozzle spacing and boom height:
- nozzle orientation
- cart speed
- wind speed

It was concluded that non-uniform coverage could be caused by damage or clogging of the nozzle or orifice. Complete coverage of the surface must be attained because even small pinholes in the membrane will increase the evaporation of moisture from the concrete. Curing compounds should be uniform and easy to maintain in a thoroughly mixed solution (Kosmatka et al 2003).

It is the goal of this research project to examine the performance of different curing compounds on the ability to reduce curling in concrete and paste specimens from differential drying. The results from different types of curing compounds, application rates, and single and double coatings are investigated.

2.2.2 EXPERIMENTAL INVESTIGATIONS

2.2.2.1 Paste Beams

2.2.2.1.1 Materials

The Portland cement used in these tests was a type I/II according to ASTM C 150, and its oxide analysis per ASTM C 114 and the phases' concentrations are shown in the following Table 4. The paste mixtures in this experiment had a water to cement ratio (w/cm) of 0.42.

**Table 4: Oxide Analysis Of The Cement Used For Paste Beams
And The Phase Concentrations**

Chemical Test Results	
SiO ₂	20.23
Al ₂ O ₃	4.77
Fe ₂ O ₃	3.23
CaO	64.15
Phase concentrations	
C ₃ S	70.69
C ₂ S	4.68
C ₃ A	7.18
C ₄ AF	9.83

Three different curing compounds were used in this project; these products were chosen as they were from different chemical families and were used by three different states. The standardized specifications are summarized in Table 5 according to the MSDS for the product. The first curing compound (C1) is high solids, white-pigmented, and Poly-alphamethylstyrene-resin-based and it dries in approximately one hour. The second

curing compound (C2) is a water-based, white-pigmented curing compound series; it has resin-based dispersions with selected white pigments and typically dries in 1-2 hours. The third one (C3) is of a water-based, white-pigmented concrete curing compound series, with a wax-based dispersions and selected white pigments and typically dries in two hours.

Table 5: Curing Compound Specifications

Curing compounds	Type (Per ASTM C 309)	Drying time	Basis
C1	Type 2, Class B	1 hour	Poly-Alphamethylstyrene
C2	Type 2, Class B	1-2 hours	Water-Based, Resin-Based
C3	Type 2, Class A	2 hours	Water-Based, Wax-Based

2.2.2.1.2 Sample Preparation And Methods

The paste mixtures were prepared according to ASTM C305. Three paste beams with dimensions of 39.4" x 2.4" x 0.5" were prepared in plastic molds from each mixture. For this testing, all specimens were stored in an environmental chamber at 73° F and 40% relative humidity. All specimens were cured using wet burlap for 5 hours before being covered in curing compound. Before and after the application of the curing compound, the samples were weighed and finally stored in the chamber room until 24 hours after mixing. Next the samples were demolded, weighed, sealed with wax on all sides but the finished surface, reweighed and stored on their sides in the chamber room. Figure 24 shows the specimens covered with different curing compounds inside the chamber room. This test was adopted from previous work done by Burke (2004) to investigate the effectiveness of shrinkage reducing admixtures.



Figure 24: The Specimens Covered With Curing Compounds And Stored In The Chamber Room

2.2.2.1.3 Test Procedure And Measurement

For this testing the three different types of curing compounds were applied 5 hours after casting. This time period was chosen as it was the time required for the bleed water to disappear from the surface of the specimen. Each curing compound was applied in three different volumes. A coverage that was about equal to the manufacturer's recommended dosage was used, as well as ones that were about 50% lower (low dosage) and 50% higher (high dosage), were used to evaluate the performance of different curing compounds and coverage. The curing compound was applied in a single layer with a Chapin 5797 flat nozzle for all products with a pump pressure of 40 psi, as suggested by the manufacturer. To modify the application of the compounds, three different nozzle distances were used with the same cart velocity as suggested by Vandebossche (1999). For this purpose, a cart was constructed that runs on tracks and holds the nozzle at a controlled height. The cart was moved along the sample at a constant velocity. This constant velocity was obtained by using a metronome and marks with a known distance on the track. The cart was moved so that it crossed a mark at the exact same time the metronome sounded. Because the metronome supplied a beat at a constant interval, and the cart operator was able to move between the marked locations at a constant rate then this allowed the cart to move at an almost constant velocity. This velocity could be easily changed by changing the rate of the metronome. For all testing the velocity was kept constant and the coverage rate was adjusted by changing the height of the spray nozzle.

The coverage rate on samples cured by the curing compound was determined by the following Equation 5 (Vandebossche 1999):

$$\text{Equation 5: } v = \frac{\text{Coeff.} * F}{C * w}$$

Where:

v = Cart speed, kilometers per hour (miles per hour)

Coeff. = 6 when using SI units (0.13636 with Imperial)

F = Flow rate, liters per minute per nozzle (gallons per minute per nozzle)

C = Desired coverage, liters per square meter (gallons per square foot)

w = Nozzle spacing, cm (inches)

The following picture in Figure 25 shows the schematic view of the spray coverage calculated by Equation 5. This equation is commonly suggested by the curing compound manufacturers to determine the correct coverage rate.

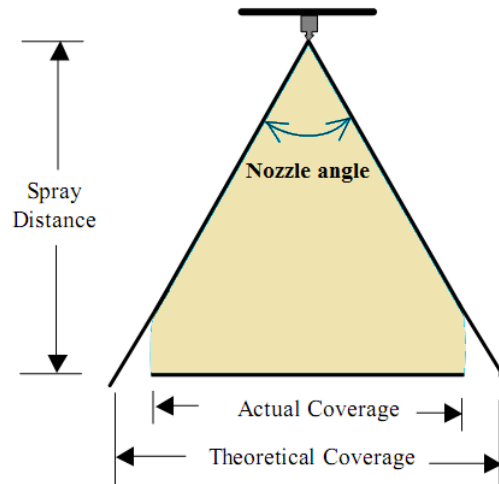


Figure 25: Schematic View Of The Spray Coverage

The flow rate, cart speed, desired coverage, and spray distance used in this study to spray the curing compounds were computed by the equation. The velocity applied for all dosages was 1.33 ft./sec and the coverage time was 2.5 seconds; thus, the spray distances were 20.85", 10.40", and 6.95" for low, medium, and high dosages respectively.

To check the uniformity of the coverage and accuracy of the equation, some practice tests were done by using steel plates of known areas that were placed at a known height. These plates were weighed before and after applying curing compounds. By using the area of the plate and the weight of the curing compound the coverage could be calculated. A summary of the amount of applied curing compound and the standard deviation for each test is shown in Table 6.

Table 6: The Curing Compound Coverage And Standard Deviation

Curing method	Basis	(gal/ft ²)	low	medium	high
C1, Single layer	Poly-Alphamethylstyrene	Coverage	0.0019	0.0040	0.0051
		STD	0.0002	0.0001	0.0000
C2, Single layer	Water-Based, Resin-Based	Coverage	0.0020	0.0037	0.0051
		STD	0.0001	0.0004	0.0002
C3, Single layer	Water-Based, Wax-Based	Coverage	0.0036	0.0048	0.0074
		STD	0.0001	0.0001	0.0003
C3, Double layer	Water-Based, Wax-Based	Coverage	0.0027	0.0041	0.0056
		STD	0.0001	0.0001	0.0003
1-day wet + C3 Single	Water-Based, Wax-Based	Coverage	-	0.0038	-
		STD	-	0.0002	-

A double layer of C3 was tested as well. This application was achieved by applying two layers whose sum would equal the required value. Also, the combination of 1 day wet curing and a medium application rate of C3 was tested.

The measurement of the beam deflection over time and its weight change were explained previously. For the length change two ends of the specimen are attached to a flat aluminum plate with the uncoated surface facing the plate to measure the curling deflection with a caliper that is accurate to 0.0005". The weight of the sample is also measured with time using a scale that is accurate to 0.1 grams.

2.2.2.2 Concrete Beams

2.2.2.2.1 Materials

The cement, aggregate, fly ash, and moisture barrier used in this experiment were the same as in described previously for concrete beams. Materials include cement type I according to ASTM C 150 and dolomitic limestone and natural sand aggregates as well as a Class C ASTM C 618 fly ash. To seal the concrete beam samples, a synthetic moisture barrier was used as a form liner. The interface between the beam and the water membrane was sealed with hot glue to ensure a good bond was maintained throughout the test. The cement chemical analysis per ASTM C 114 and the phases' concentrations are shown in the following Table 7.

Table 7: Chemical Analysis Of The Cement Used For Concrete Beams And The Phase Concentration

Chemical Test Results	
SiO ₂	21.13
Al ₂ O ₃	4.71
Fe ₂ O ₃	2.55
CaO	62.06
Phase concentrations	
C ₃ S	52.14
C ₂ S	20.22
C ₃ A	7.69
C ₄ AF	7.96

2.2.2.2.2 Mixture Proportions And Methods

The mixture proportion and the mixture procedure were explained in chapter 2.1. However, this concrete was not air entrained. The water to cement ratio used in this experiment was equal to 0.41 for concrete beams. All of the aggregate, both coarse and fine, were charged into the mixer along with approximately two-thirds of the mixing water. The combination was mixed for three minutes. Next any clumped fine aggregate was removed from the walls of the mixer. Then the cement was loaded into the mixer,

followed by the remaining mixing water. The mixer was turned on for an additional three minutes. Once this mixing period was complete, the mixture was left to “rest” for the following two minutes while the buildup of material along the walls of the mixer was removed. Next the mixer was started and the admixtures were added and the mixer was allowed to run for the remainder of the three minutes (ASTM C 192). The slump (ASTM C 143), unit weight (ASTM C 138) and the air content (ASTM C 231) were measured.

2.2.2.2.3 Sample Preparation, Casting And Curing

In this experiment the size of the concrete specimen investigated was 7.5'×6"×8", with all sides sealed with a synthetic moisture barrier except the top surface for each specimen. These specimens were all stored on their side in an environmental chamber at 73° F temperature and 40% relative humidity. After placing and vibrating the concrete in 3 different layers, the top surface was made flat with a screed. Next a micro-surface was applied with a burlap drag, and then the surface was finally tined using a comb. The comb had transverse grooves 1/16" wide, 1/4" deep, and center to center spacing of 1" between the tines based on ODOT Standard Specification for Highway Construction. For this testing only curing compounds C3 and C1 were investigated. A single layer of C3, single layer of C1, and a double layer of C3 were investigated in this experiment. The layers were applied in two equal coatings so that their sum equaled the total desired coverage. The beams were flipped on their sides and placed on wooden dowels after 24 hours. This was done to minimize the influence of gravity on the results. After placing the beam on its side, it was fixed at the end with a C-clamp, steel plates, and rubber bearing pads.

2.2.2.2.4 Test Procedure And Measurement

The RH was measured 5 days after casting. DS1923 Hygrochron Temperature/Humidity Logger iButton sensors were used to measure RH at 4 different distances: 0.5", 1", 3", and 5" from the finished surface.

The curling height of the beam was measured at two different locations: 45", and 89.5" from the end of the beam. The deflection gauges were fixed using magnets on the steel support beneath the concrete beam. The accuracy of this gage was 0.0005". Also, the surface strain of the beam was measured after flipping the beam. Curing compound was sprayed on the samples about 2 hours after casting with a similar method as with the paste beams. In order to obtain the desired coverage, many repetitions were completed and checked with steel plates. This allowed for very precise nozzle height and speed to be found that corresponded to a known amount of coverage. The amount of compound used for these experiments was chosen as 5.0 m²/L (200 ft²/gal) based on the ASTM C 309; therefore, the double layer with C3 (C3, D, medium) was performed in two different layers each with 100 ft²/gal coverage.

2.2.3 EXPERIMENTAL RESULTS

2.2.3.1 Paste Beams

Figure 26 and Figure 27 show weight losses and deflection over time, respectively, for different application rates of curing compound C2. Label “C2, S, low” means a single layer of C2 in medium rate and so on. These values are shown as they are typical results for one of these tests.

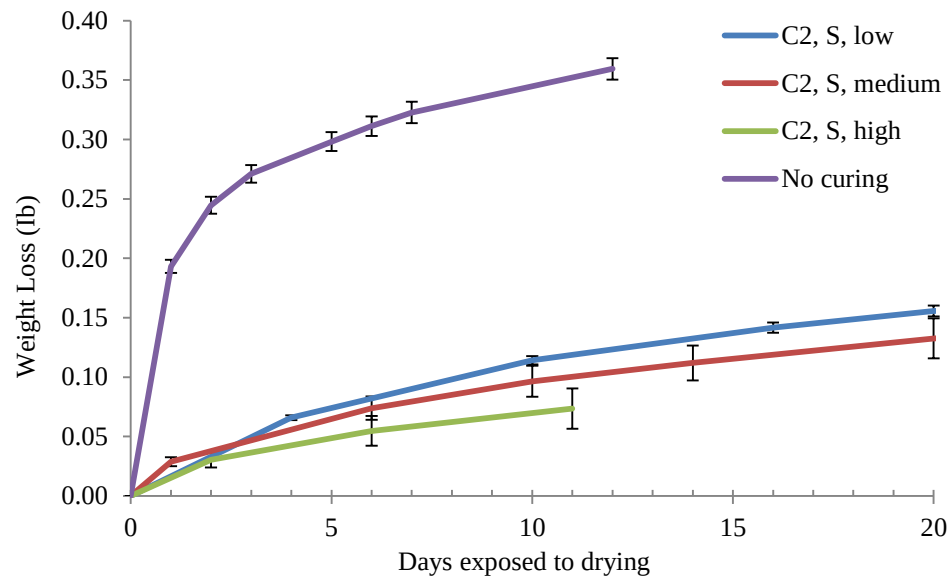


Figure 26: Moisture Loss For A Paste Beam vs. Time For C2 In Single Layer Compared To No Curing Method

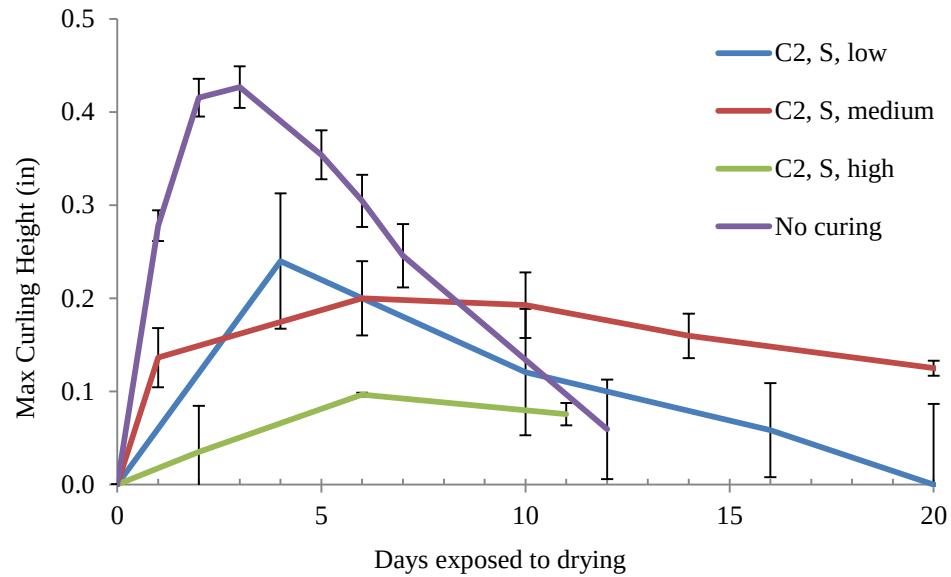


Figure 27: The Maximum Curling Height vs. Age For C2 In Single Layer Compared To No Curing Method

Figure 28 summarizes the deflection results for all curing compounds and shows the maximum deflection that the specimen experienced versus the application rate of different curing compounds. Also included in the graph is a line showing the deflection for a specimen with no curing compound, one day of wet curing, and a specimen that was cured for 1 day and covered with a single layer of curing compound C3. Also, the graph includes the maximum curling height for 1 day of wet curing to be compared and discussed later.

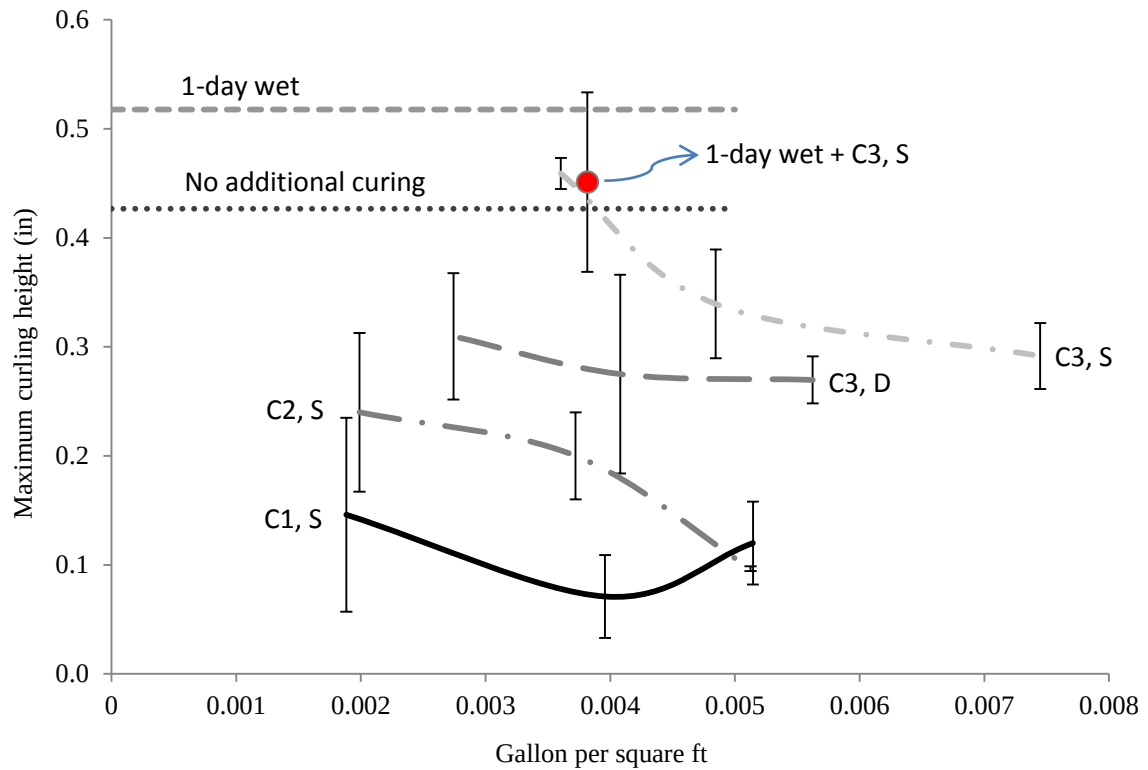


Figure 28: Comparison Between Highest Deflections vs. Different Coverage Of Curing Compounds On Paste Beams

Figure 29 shows the weight loss versus the coverage after 11 days for the different applications of curing compounds. The graph is shown at 11 days because this provided a good amount of time for drying and this measurement existed for all of the data.

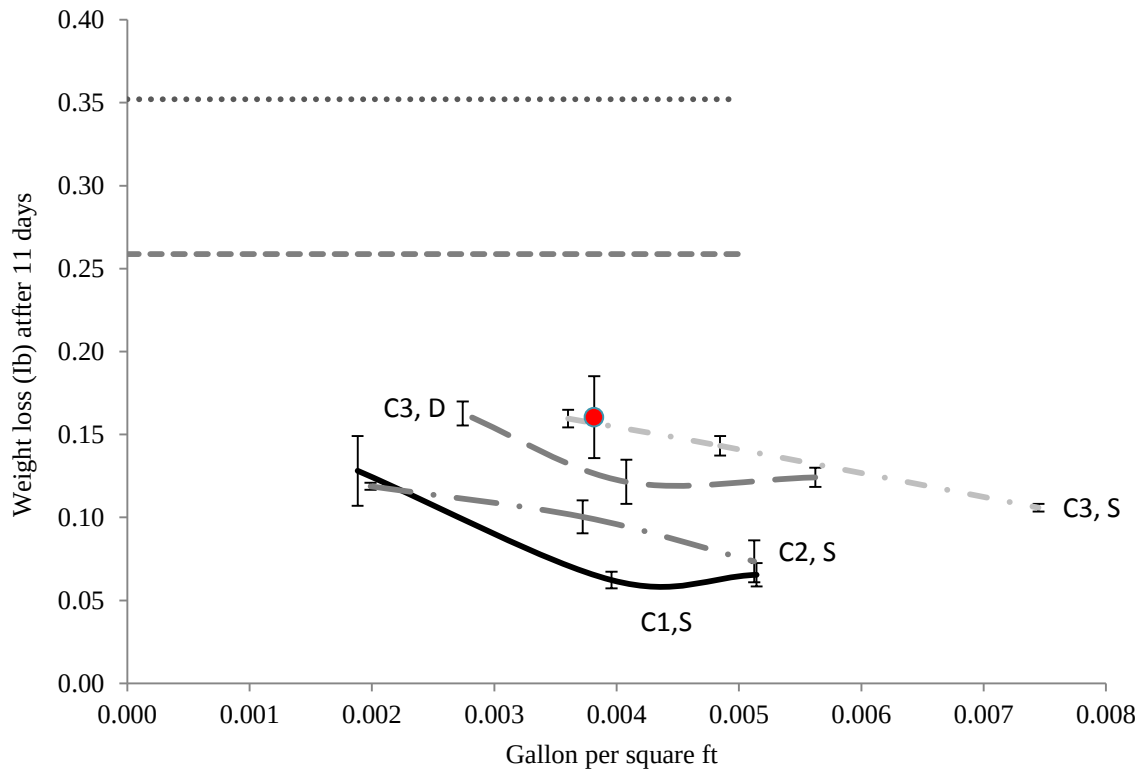


Figure 29: Comparison Between Weight Losses vs. Different Coverage Of Curing Compounds On Paste Beams After 11 Days

Figure 30 and Figure 31 show the maximum curling deflection and the weight loss after 11 days versus additional curing time for the wet cured specimens in comparison with specimens cured with curing compounds. A number of curing compound techniques of interest have been included including a single layer of C3 with a medium application. Also, graphs include the combination of 1-day wet curing with a single layer of C3 in medium application rate to be compared later.

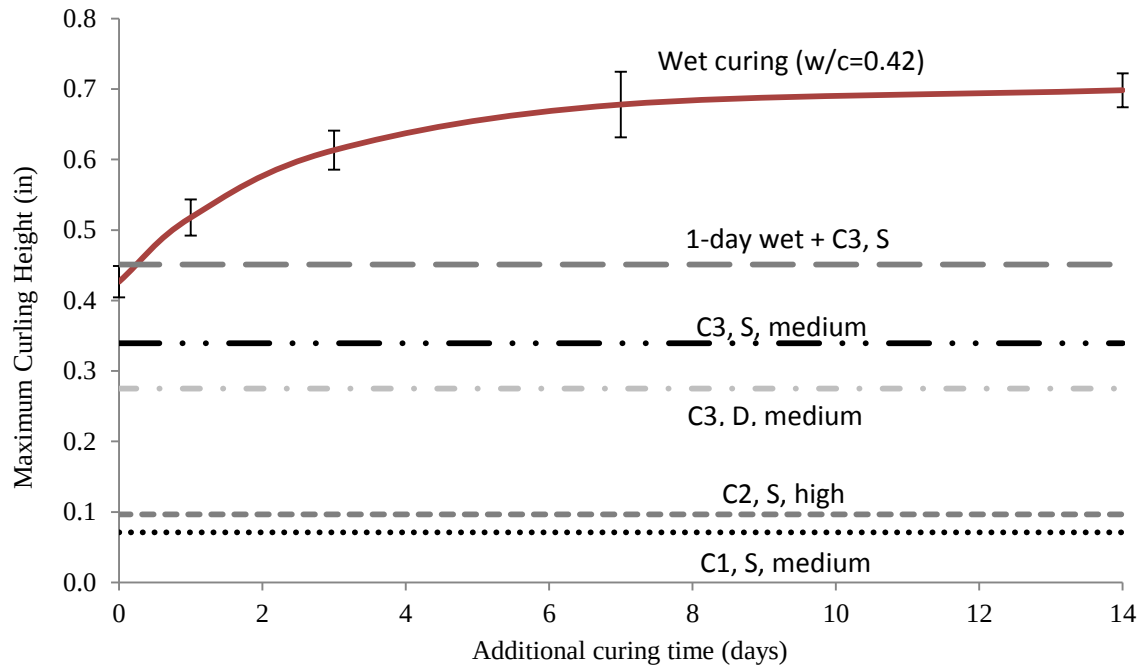


Figure 30: The Maximum Deflections Of Wet Cured Paste Beams vs. Additional Curing Time Compared To Curing Compound Methods

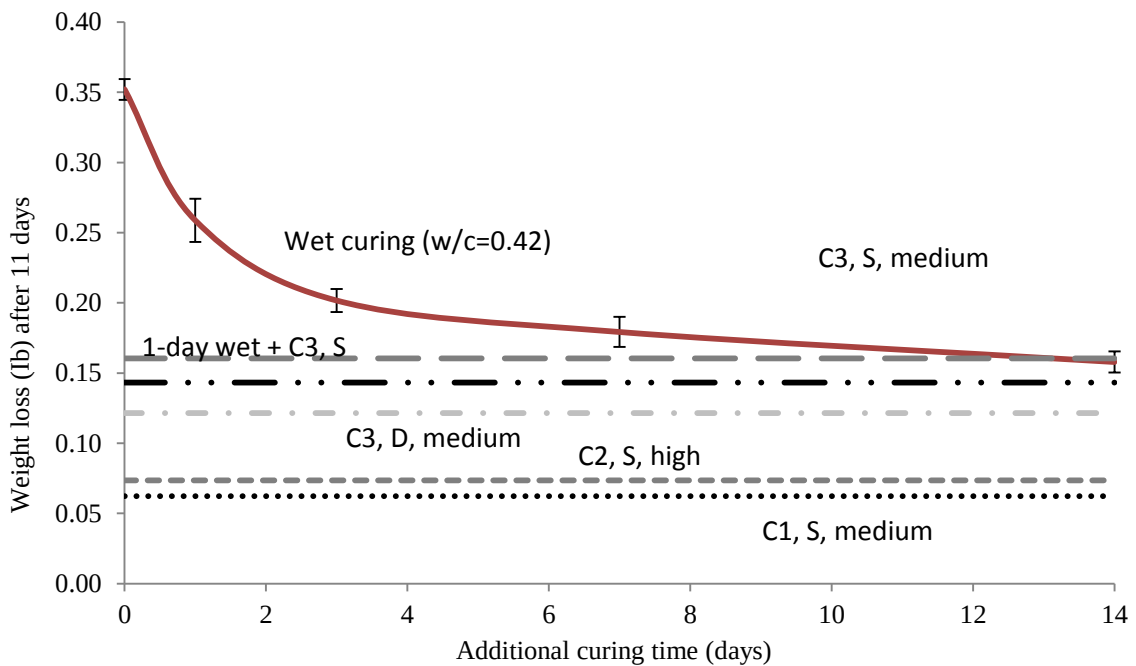


Figure 31: The Weight Losses Of Wet Cured Paste Beams After 11 Days vs. Additional Curing Time Compared To Curing Compound Methods

2.2.3.2 Concrete Beams

Figure 32 shows the surface strain of the concrete beams with different curing compounds compared to those with no curing.

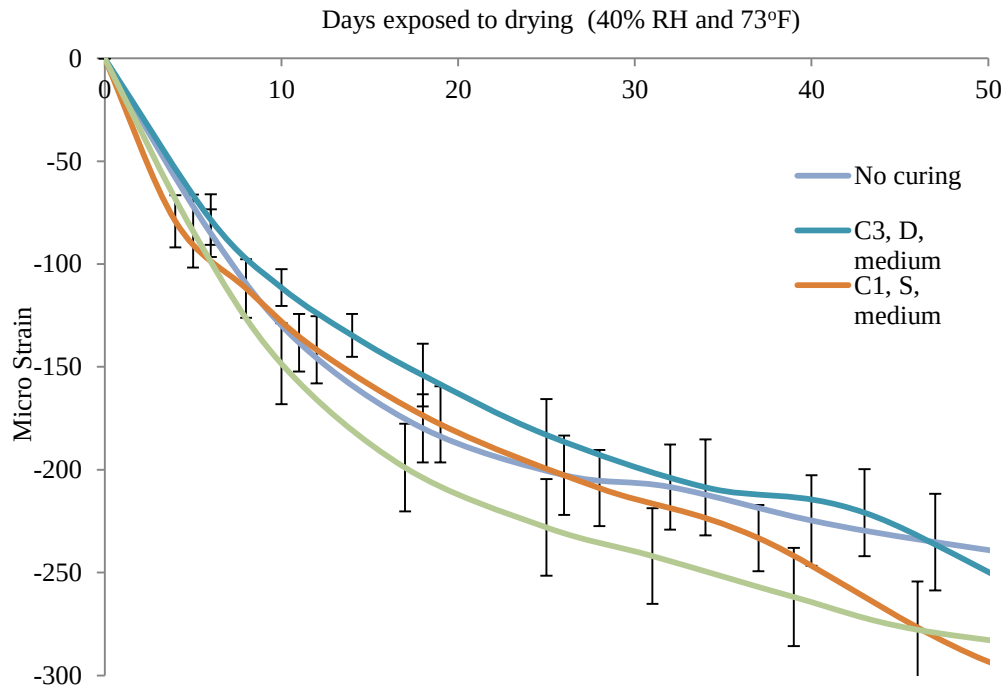


Figure 32: Surface Strain Of The Concrete Beams With Curing Compounds vs. Time

Figure 33 and Figure 34 show the typical graphs for the relative humidity of the beam during the exposure and RH profiles at different depths of the beam with a double layer of C3.

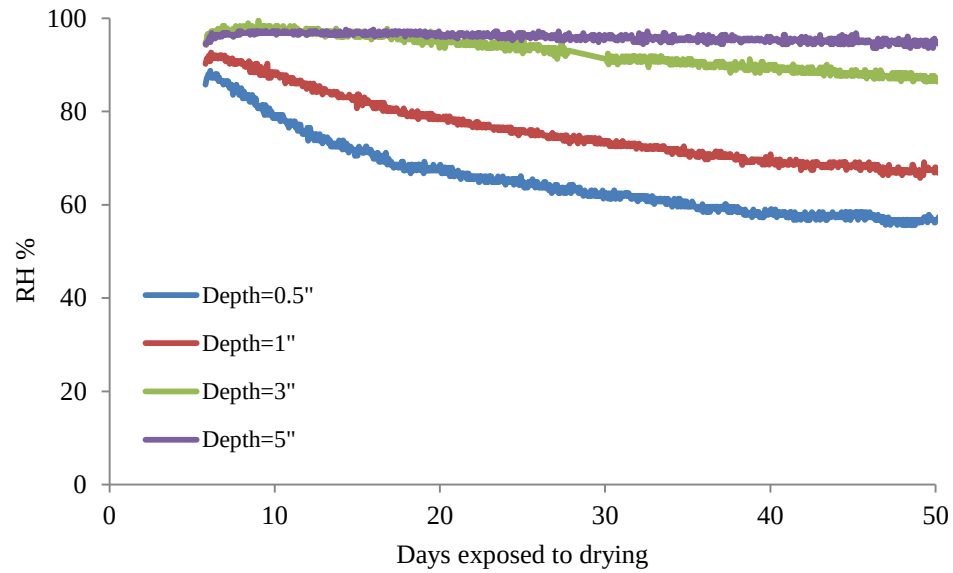


Figure 33: Relative Humidity At Different Depths Of Concrete Beam C3-D During The Age

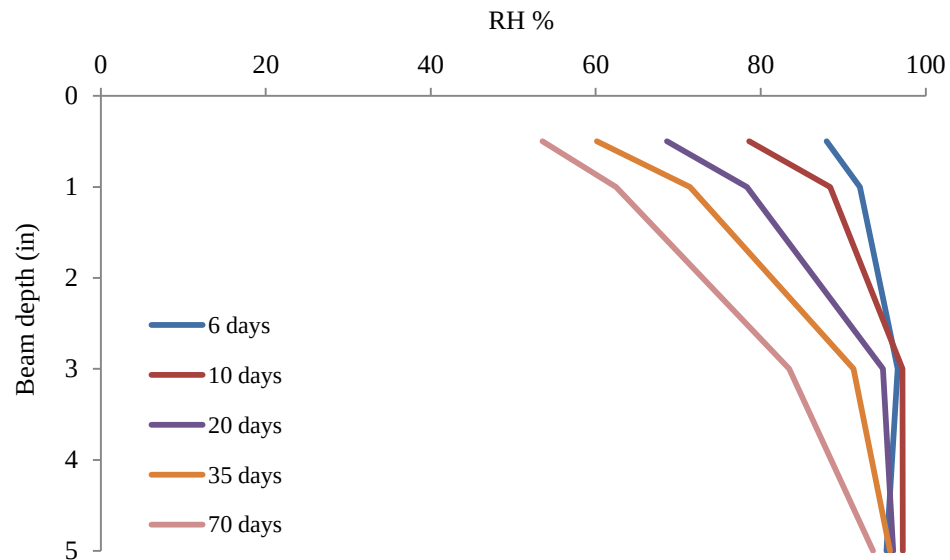


Figure 34: RH Profiles For 6, 10, 20, 35 And 70 Days After Exposure For Concrete Beam C3-D

Figure 35 shows the area under the relative humidity profiles for the abovementioned beams over the age after exposure; however RH measurement was started 5 days after casting due to the concerns about early age performance of the RH gages.

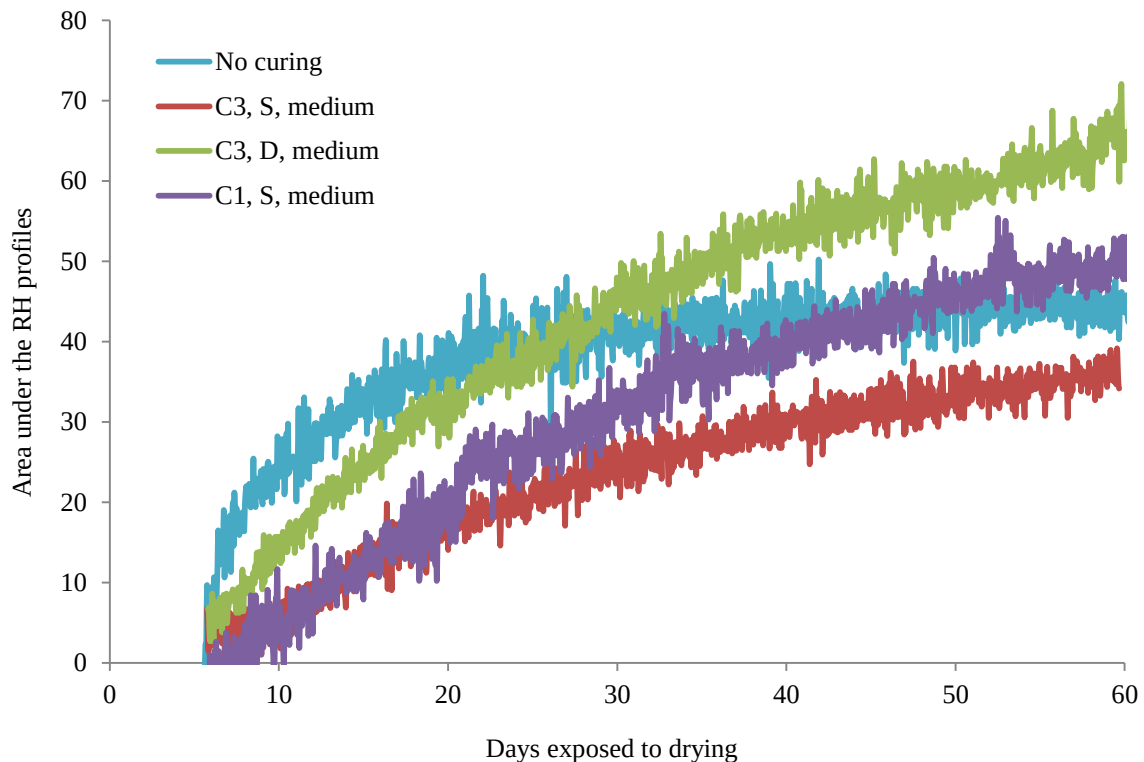


Figure 35: Integrated Area Under The RH Profiles vs. Time For Concrete Beams

2.2.4 DISCUSSION

2.2.4.1 Paste Beams

Figure 26 shows that the curing compound C2 has reduced the water loss when compared to the specimen with no curing. As the application increased the curling decreased. Figure 27 shows curling height is less with a higher coverage of curing compound compared to no curing. The curing compound retains the moisture content for a longer age by making a thin membrane, but it does not terminate the loss of moisture completely.

In Figure 28 it can be seen that, typically, as the amount of curing compound applied increased, the maximum curling height of the specimen decreases. The C3 curing compound in a single layer reduces curling with higher application rates; however, the low application rate of C3 in a single layer had a very similar amount of curling as the sample with no curing compound. The deflection from the samples with 1 day of additional wet curing plus a single layer of C3 also had a similar performance as the sample with no curing. There is a slight improvement over the sample with 1 day of wet curing. The double layer of C3 shows a slight reduction in curling from the increase in

the curing compound application. Of the samples investigated, it was surprising that there was not much improvement in performance with an increase in the application of the curing compound. The increase in application of C2 also decreased the maximum deflection. Finally, the increase in application rate of C1 also did not show much of a difference. It was observed that the effectiveness of a curing compound has some limiting value in three of the different experiments. It appears that a curing compound has a certain application thickness that is needed to ensure effectiveness. If more curing compound is applied than this limit value, then there is not much benefit in the performance. Furthermore, it appears that a double layer of curing compound reaches threshold limit at a lower volume of curing compound application than a single layer of curing compound. This probably is associated with the increased effectiveness in coverage for a double application of curing compound.

Figure 29 shows that all of the specimens after 11 days of drying that used curing compounds had a lower loss of moisture than those that did not. The moisture retention capability of the single layer of curing compound was the highest with C1 and the lowest with C3. The double layer of C3 did show an improvement in performance over the single layer. This data suggests that a curing compound does a much better job of keeping the water inside of the paste specimen than other methods. Also it appears that some curing methods are more effective than others at keeping moisture in a sample.

Figure 30 shows that each of the curing compounds has the ability to reduce curling below levels of wet curing in the specimen. It can also be seen that the prolonged wet curing increased the curling of the specimen as discussed in chapter 2.1. Figure 31 shows that after 11 days of drying that all of the curing methods were able to keep the moisture loss less than the specimen that had the 14 days of wet curing or less. This ability to keep moisture in the specimen helps to minimize the curling from the differential shrinkage. Figure 31 also validates that the best curing compounds always have the least water loss and that even more additional wet curing only increases the water content and shrinkage possibility due to the finer pore structure compared to curing compounds.

The combination of 1-day wet curing plus curing compound C3 when compared to 1-day wet curing method shows that rapid drying of the surface of the samples that did not contain curing compound should be avoided. The best curing environment is to keep the concrete continuously wet during the curing period. The curing and protection should not be discontinued suddenly (ACI 224R-2001).

2.2.4.2 Concrete Beams

Figure 32 shows the double layer of C3 has the least surface strain, while the single layer of the same curing compound in the same coverage has the most surface strain. C1 in a single layer has smaller strain than C3 in a single application in the same coverage. The no-curing method curls up very slowly after about 25 days while other beams continue curling.

Some different trends were obtained in the concrete beam data than those in the paste beams. For example, sample C3, S was found to perform worse than the no curing. This was unexpected. However, the error bars for the two samples do overlap one another, and so there is no statistical difference between the results.

Although it is difficult to tell, it may be that the specimen with the single layer of C3 was not applied uniformly over the tined surface of concrete beam. Although C1 had the best performance on the paste beams, this was not the case on the concrete beams. One observation that the double layer of C3 performs better than the single layer of C1 was unexpected. This could be attributed to the ability to provide a much more uniform coverage of the double layer of C1.

Figure 33 and Figure 34 show the typical graphs of relative humidity over the depths. The RH in deeper depths decreases more slightly, and RH profiles show the speed of the RH reduction is higher for the top of the beam than its bottom.

Figure 35 shows that a no-cured sample has a faster drying rate than other beams at the early age, while samples with curing compounds have a slower drying rate. After about 25 days the slope of the drying rate of the no curing technique becomes zero, while this slope is increasing for other samples covered with curing compounds.

In the previous chapter about the paste beams it was explained that the no-curing technique has a faster water loss rate; this is true about the concrete beams, as well. The porous surface of a non-cured beam loses the construction water faster until after about a month when the curling rate seems to decrease. Other beams covered with curing compound continue curling up as long as this moisture loss rate increases, Figure 35.

2.2.5 CONCLUSIONS

Different curing compounds with different coverages were compared. The poly-alpha-methylstyrene-resin-based curing compound (C1) had the best performance with a comparable coverage rate in the paste beam tests. The water and wax based curing compound (C3) curing compound performed the worst and the water and resin based curing compound (C2) was between these two. As the coverage of the curing compound increased so did the ability to limit moisture loss and therefore curling. A double layer of a curing compound was shown to provide improved performance over a single layer of curing compound.

Curing compounds appear to limit moisture loss to a greater degree than wet curing of up to at least 14 days or no curing methods. This reduction in moisture loss seems to correspond to a reduced amount of differential shrinkage and therefore curling in the specimens investigated.

In the concrete beams it was found that the double layer of the water and wax based curing compound performed better than the poly-alpha-methylstyrene-resin-based curing compound. This is likely because it was applied in a double layer and therefore achieved

a better coverage. This is especially important for applications with textured surfaces and with conditions that are not as favorable in the laboratory. Similar suggestions have been made by Shariat and Pant (1984). The uniformity of the application of the curing compounds is an important variable that needs to be controlled.

2.3 IMPACT ON CURING COMPOUNDS TO REDUCE CURLING IN CONCRETE FROM TEMPERATURE DIFFERENTIALS

2.3.1 INTRODUCTION

Curling in concrete is affected by both temperature and moisture. Temperature gradients within concrete at setting can lead to a built in curl within a concrete pavement. This built in curl can lead to long term performance issues from cracking.

Several curing methods have been investigated to minimize the difference in the temperature gradient in the fresh concrete at setting.

The testing presented is from a scaled version of a larger slab that was allowed to hydrate outside. Larger scale tests were also completed but will be presented in the project summary report.

2.3.2 METHODOLOGY

2.3.2.1 Experiment Preparation

The preparation of the experiment consists of various tasks:

1. Preparation of formwork
2. Preparation of Burlen liners
3. Preparation of wooden thermocouple support dowels
4. Installation of Burlen liners and thermocouple dowels into formwork
5. Preparation of thermocouple wires
6. Installation of thermocouples into preassembled formwork
7. Concrete is placed

The following is a brief explanation of the procedure previously described.

The forms used are purchased steel forms. The form is divided into the two equal sections with the use of a plywood separator. The samples were 9.5"x6"x6". Two additional plywood squares are placed at either end of the forms to complete the form. The two plywood squares at the ends of the forms are sawn in half and include a ½" hole directly in the center as a means to convey the thermocouple wires for each sample. Figure 36 shows one of the steel forms with the plywood separators in place.



Figure 36: Assembled Formwork With Plywood Separators In Place

Burleen is a commercially available product which consists of a two ply fabric made of hair like fibers on one side and a moisture barrier on the other. The Burleen liners are prepared for each sample which act as a thermal and moisture barrier for all but the top surface of the sample. The liners are pre-cut in a cross like pattern and then folded to their final shape. The edges of the liners are taped together with tape to complete the liner. Figure 37 shows a Burleen liner that has been cut and taped into its final shape.

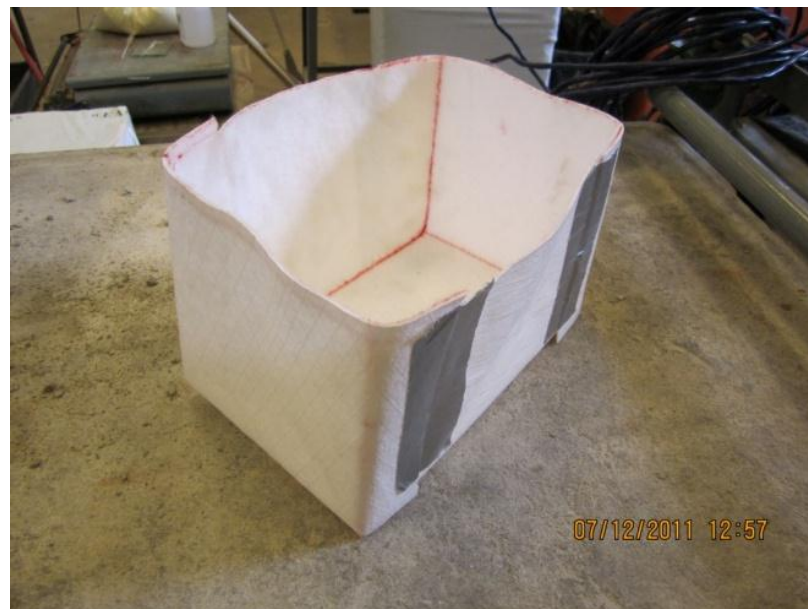


Figure 37: Assembled Burleen Liner

The wooden thermocouple dowel supports are made of a piece of laminated plywood with three holes made by a 0.5" dia. drill bit at depths of 1/2", 3" and 5-1/2" from the top of the sample. Figure 38 shows a wood dowel that is ready for use. There are also dimensions given on figure 38 which show where the holes are made relative to the outside dimensions of the dowel.

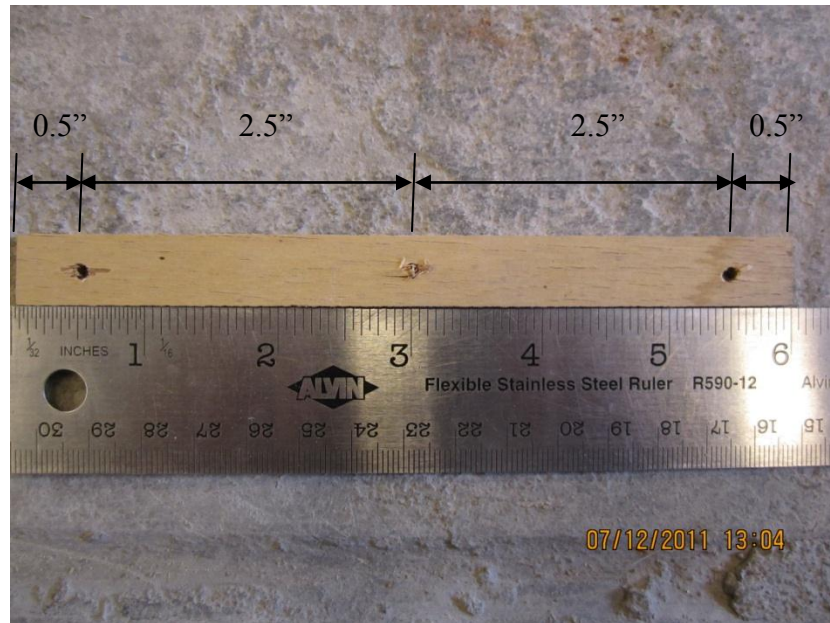


Figure 38: Laminated Plywood Dowel With Dimensions

The dowels are assembled within the liners inside the forms. The dowels are attached at the center of the sample by hot glue. Three temperature measurements were taken per sample.

Figure 39 shows the image of a completed assembly with labels.

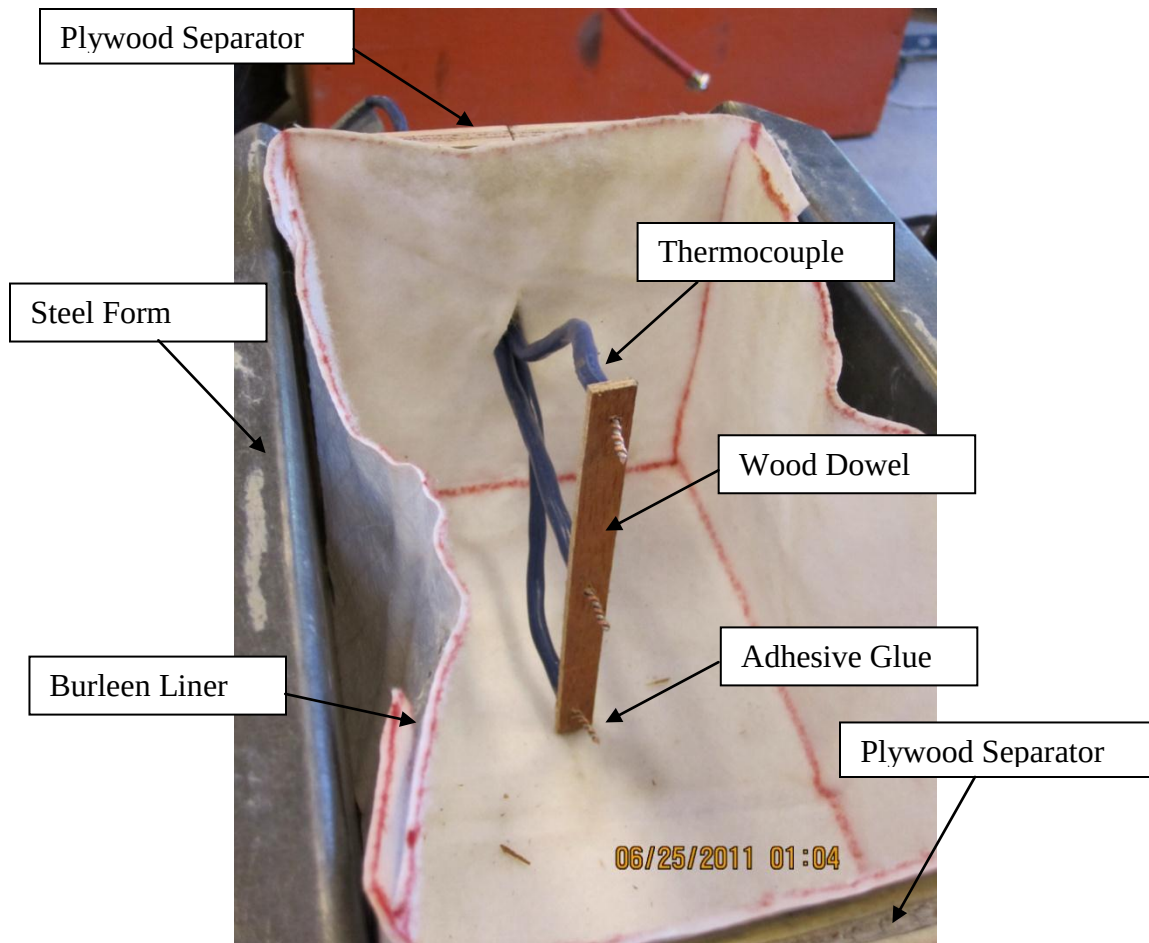


Figure 39: Assembled Thermocouple, Dowel, Liner & Form

Concrete mixtures were prepared as outlined in section 2.2.2.2 in this document.

The samples were placed with three lifts. After each lift, the sample was vibrated. Once the three lifts are placed, the samples are smoothed off to the surface of the form.

The individual samples and data recording equipment were then moved outside to a hard packed dirt surface clear of vegetation where: the forms were removed, samples spaced evenly, and the curing methods were applied.

2.3.3 DISCUSSION

2.3.3.1 Overview

A temperature gradient at different time periods was developed and compared for each sample. Ideally, a curing method should produce a near uniform gradient throughout the depth of the sample. This will minimize the temperature differential at setting and minimize the built in curl in the specimen.

During each trial, two samples of each curing method were investigated. Results from the samples were found to be very similar.

All following gradient figures show temperature gradients up until six hours. If no data is shown for the zero time segment of a figure, it is a result of the short amount of time required to configure the second data logger after the first is completed and recording data.

2.3.3.2 Curing Methods Tested

In the following test, the focus was on the ability for a covering to insulate the concrete.

Six investigations were made consisting of varying combinations of curing methods. If methods were determined to be minimally effective at insulating the samples, then further testing of those methods was not pursued.

The most informative data from the six investigations is presented in the following. More findings will be presented in the Phase 1 summary report.

The methods investigated and reported here are:

1. No Cure (control method)
2. Misting
3. Single Layer of Curing Compound
4. Two Layers of Wet Burlap
5. Two layers of Wet Burlap covered by One Layer of Blue Tarp
6. Two layers of Wet Burlap covered by One Layer of Clear Plastic
7. Two layers of Dry Burlap
8. Six Layers of Dry Burlap
9. One Layer of Burleen

On the following figures, there are dashed designation lines which represent temperatures at various depths of the sample. The two designators named Air and Ground represent the ambient air and ground temperatures immediately above and beneath the sample.

2.3.3.3 No Curing Method

This method is considered the benchmark between all of the other tests. Conventionally this is thought to be the worst curing situation. The samples where no curing techniques were used showed that initially the samples surface remained cooler than the ground temperature. At three hours, the greatest difference in the temperature at the surface versus the rest of the sample can be seen. Afterward the sample begins to cool in a relatively uniform manner as the surrounding temperatures lessened. Figure 40 shows the temperature gradients for the no cure method.

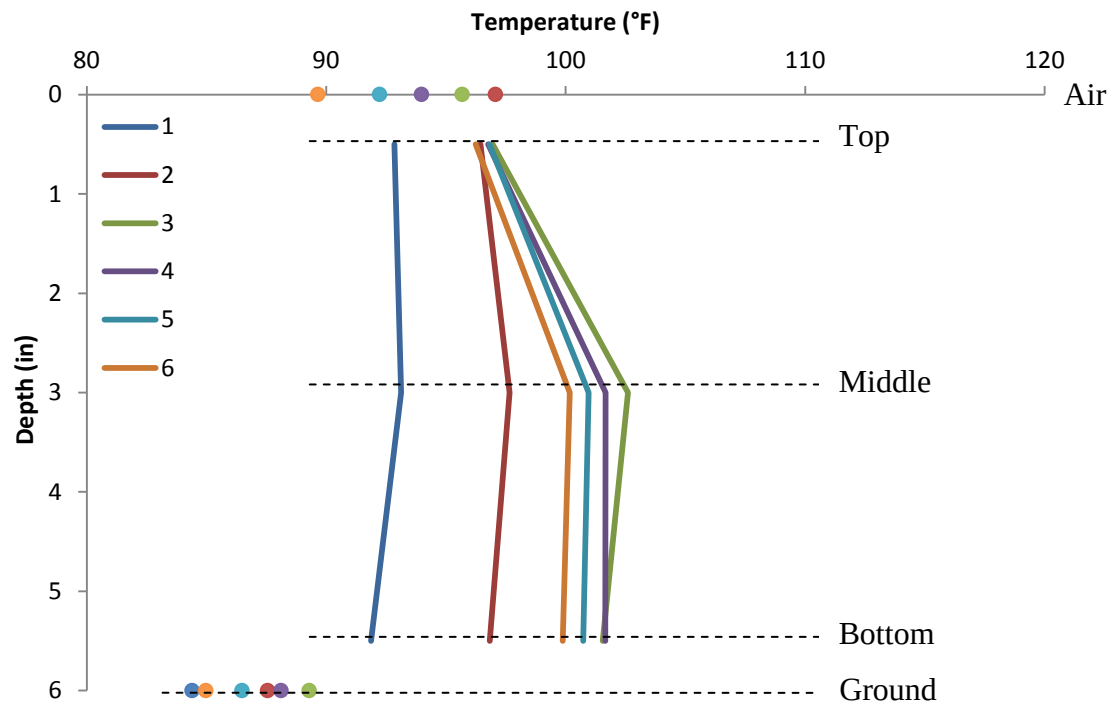


Figure 40: No Cure Temperature Gradients

2.3.3.4 Misting

The misting procedure used for curing involved applying a fine water spray to the sample surface once per hour for six hours after placement. There is not a noticeable difference at the surface of the sample that can be attributed to the misting process. There is little difference between the no curing and the misting sample. This is likely because the misting is not a large enough volume to make an impact on the mass of concrete. Figure 41 shows the temperature gradients for the misting method.

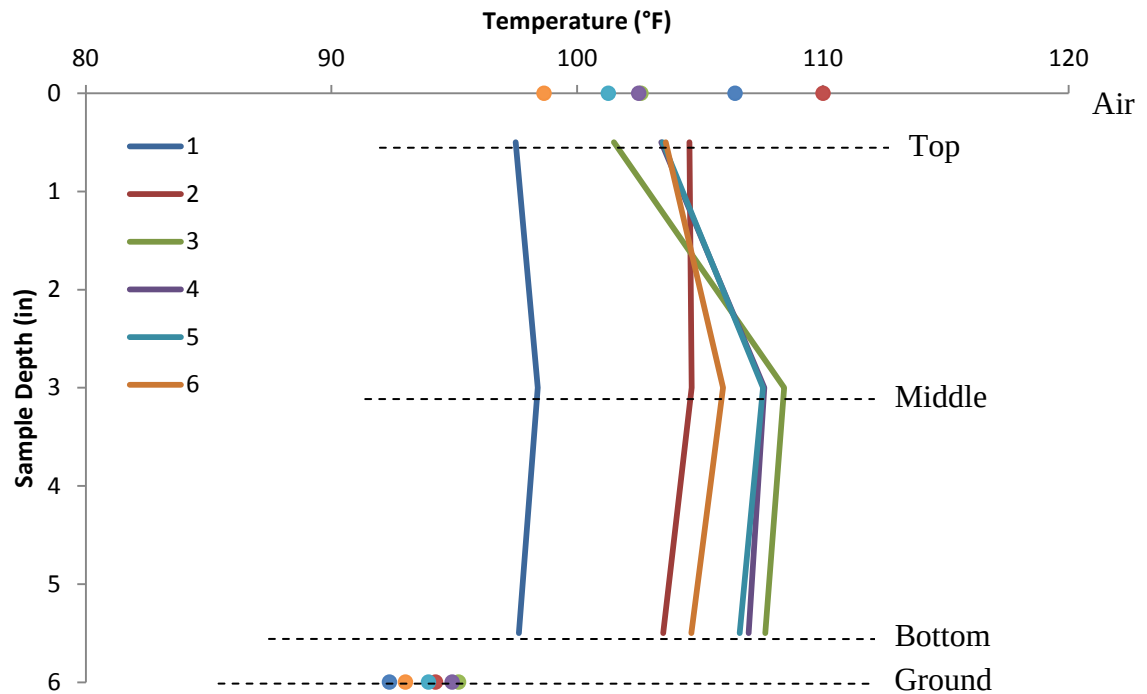


Figure 41: Misting At Hourly Intervals For 6 Hours After Placement Temperature Gradients

2.3.3.5 Curing Compound

There was little difference between the no cure , misting, and curing compound sample. The surface of the sample was slightly warmer in the sample with the curing compound. This is probably due to the reduced amount of evaporation from the sample. Figure 42 shows the temperature gradients for the curing compound method.

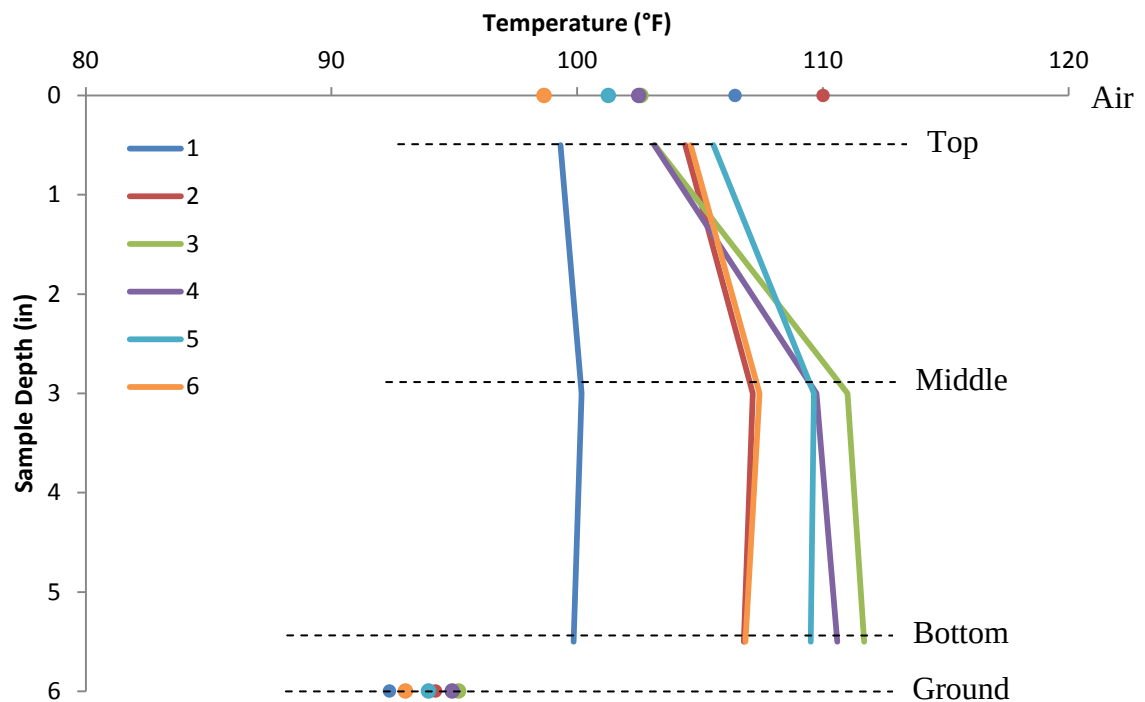


Figure 42: Single Layer Curing Compound Temperature Gradients

2.3.3.6 Two layers of Wet Burlap

Wet burlap showed a much more uniform temperature gradient than all of the other previous curing methods investigated. The burlap likely acts as a covering that minimizes surface evaporation and also insulates the sample. Figure 43 shows the temperature gradients for the two layers of wet burlap method.

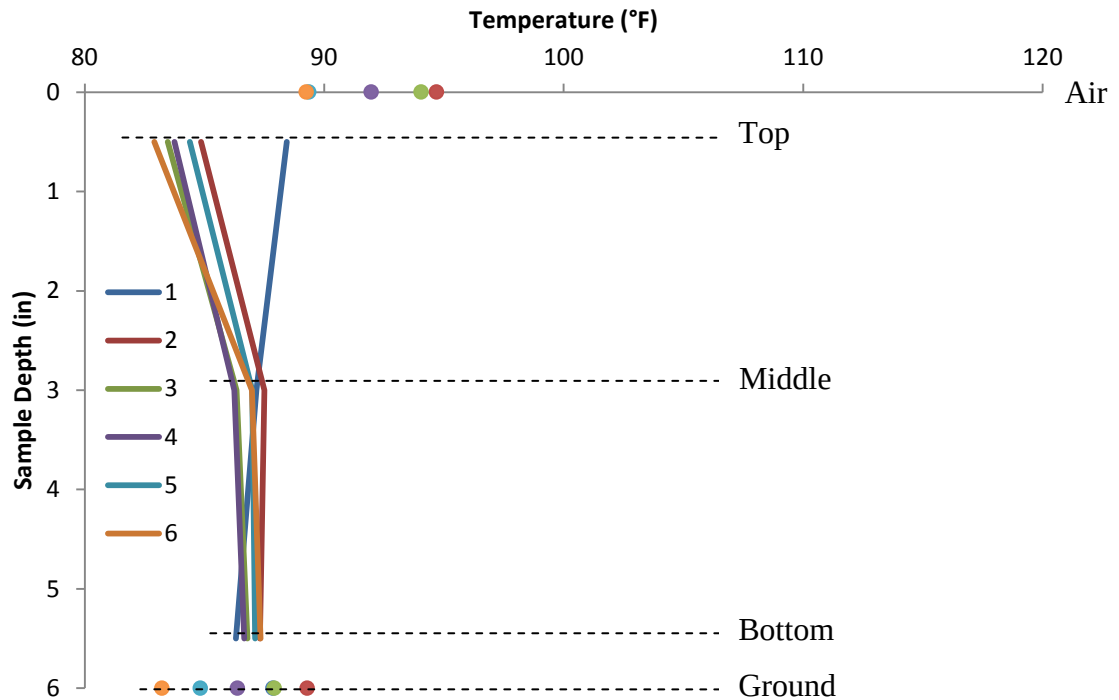


Figure 43: Two layers Wet Burlap Temperature Gradients

2.3.3.7 Two layers Of Wet Burlap Covered By One Layer Of Blue Tarp

The sample where wet burlap was covered with blue tarp kept the surface of the sample much hotter than the rest of the samples. During the last three hours the middle of the sample became the hottest portion of the sample. Also, as the surface heats then cools, the bottom of the sample continuously heats. The tarp used is a woven material which does not let the air near the sample. Figure 44 shows the temperature gradients for the two layers of wet burlap covered with a single layer of blue tarp.

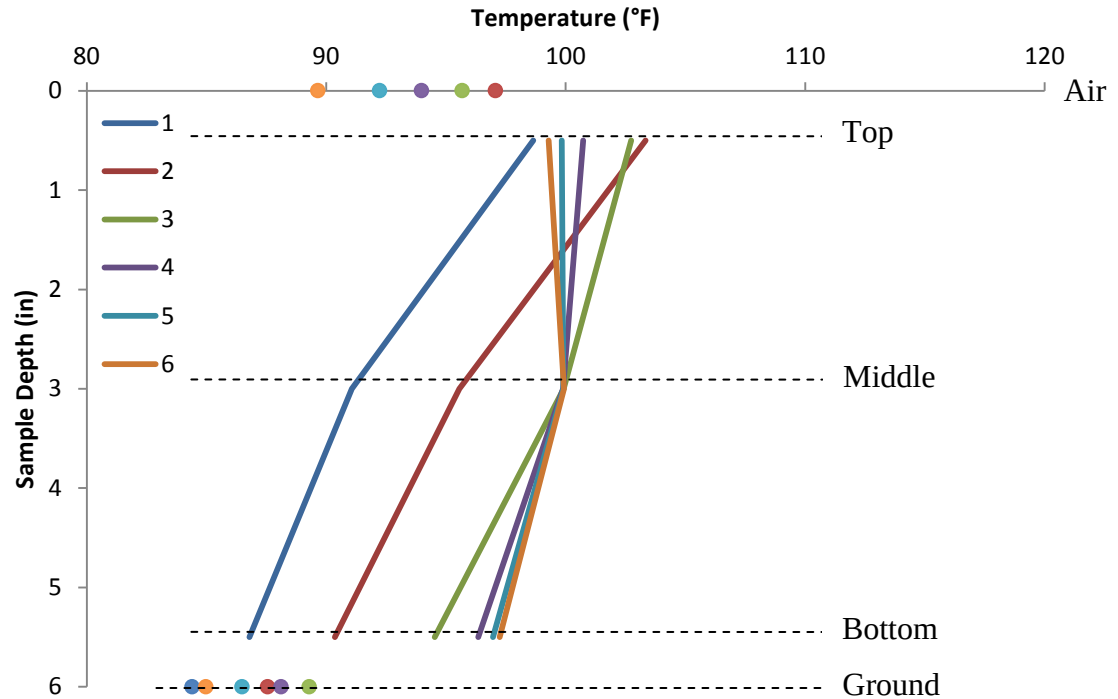


Figure 44: Two layers Wet Burlap & One Layer Blue Tarp Temperature Gradients

2.3.3.8 Two layers Of Wet Burlap Covered By One Layer Of Clear Plastic

The use of wet burlap with a clear plastic covering showed different temperature gradients at different times. The top material became very hot during the testing. The wet burlap seemed to insulate the concrete. Figure 45 shows the temperature gradients for the two layers of wet burlap covered with a single layer of clear plastic.

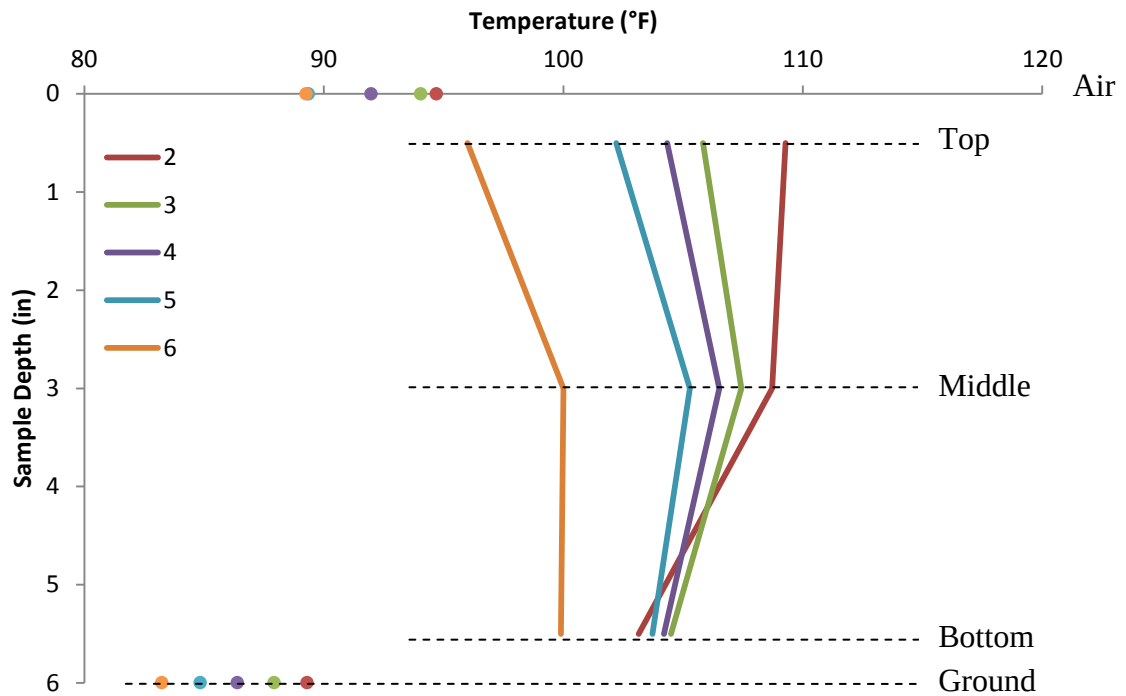


Figure 45: Two layers Wet Burlap & One Layer Clear Plastic Temperature Gradients

2.3.3.9 Two layers Of Dry Burlap

Dry burlap showed very uniform gradients during curing. The gradients here are quite constant after second hour of curing and show a uniform temperature variation throughout the sample. Figure 46 shows the temperature gradients for the sample with two layers of dry burlap.

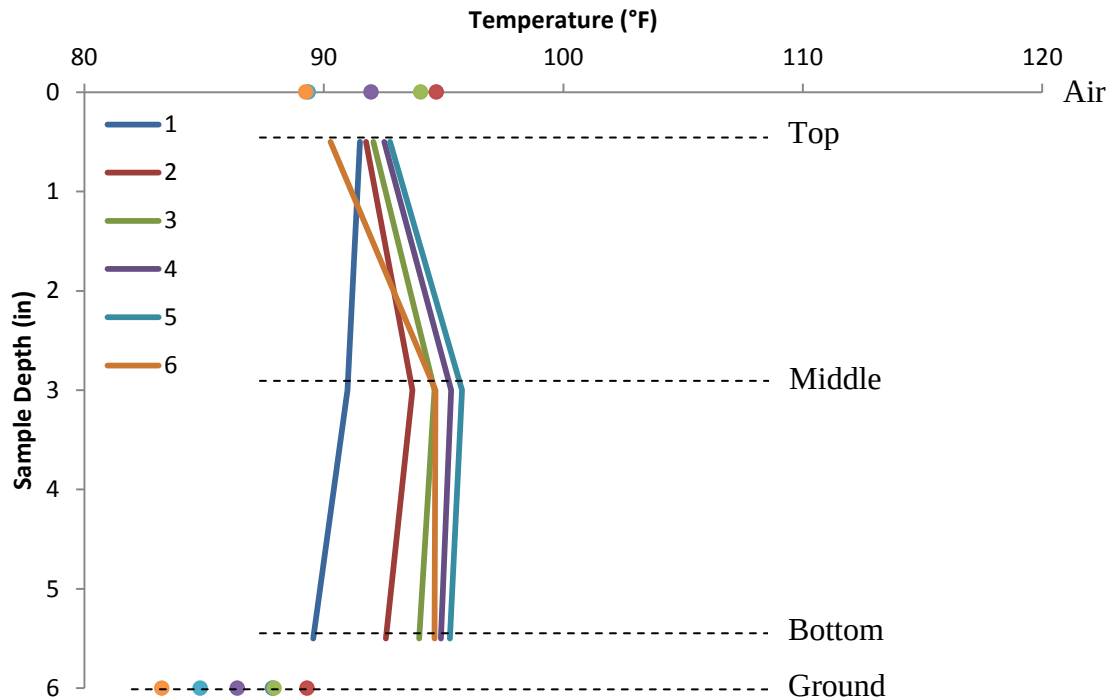


Figure 46: Two layers Of Dry Burlap Temperature Gradients

2.3.3.10 Six layers Of Dry Burlap

This method showed very acceptable gradients by the standards of the current methodology. The temperature continues to rise throughout the measured time interval, however unlike other methods; the samples keep a uniform temperature gradient. While not completely vertical, the gradients are very constant showing that the curing method allows the sample to maintain constant temperature changes in relation to its depth. It is believed that this uniformity is due to air layers between the layers of breathable fabric. These air layers act much like other technologies (ex. layered glass windows in homes) where they insulate the two sides by allowing more gradual changes in temperature. Figure 47 shows the temperature gradients for the six layers of dry burlap method.

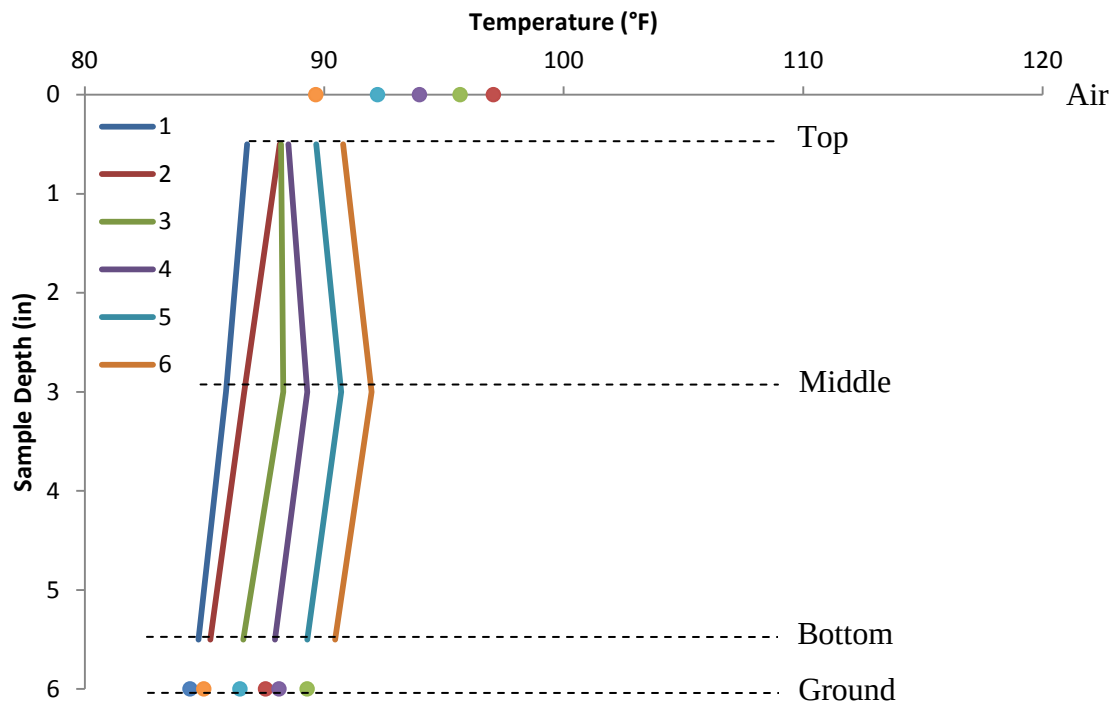


Figure 47: Six Layers Of Dry Burlap Temperature Gradients

2.3.3.11 One Layer Of Burleen

The last method tested is a single layer of Burleen. Note that all samples are lined on five of their six sides with Burleen already. This method essentially seals the entire sample with continuous material. This method shows similar trends to other tested methods where the sample heats and then begins to cool after the third hour of curing. This technique provided a uniform curing gradient. Figure 48 shows the temperature gradients for a single layer of Burleen.

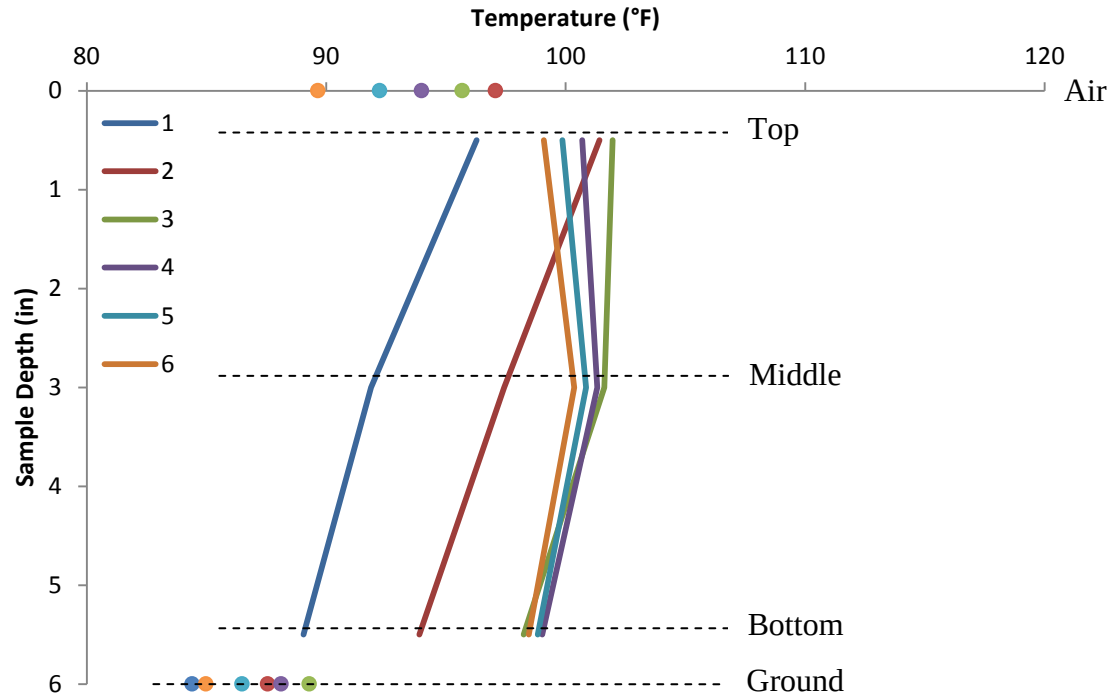


Figure 48: One Layer Of Burleen Temperature Gradients

2.3.4 RESULT COMPARISSON

Table 8 shows the temperature differences of the top and bottom of the samples at two hour intervals beginning at placemen.

Table 8. Differences In Temperature Between The Top And Bottom Of Investigated Samples At 2, 4 And 6 Hours After Placement

Curing Method	Investigation Date	Temperature Differences (°F)		
		2 (hr)	4 (hr)	6 (hr)
No Cure	6/10/2011	0.38	4.89	3.64
Misting	7/26/2011	1.07	3.56	1.04
Curing Compound	7/26/2011	2.38	7.45	2.23
Two Layers Wet Burlap	6/10/2011	2.45	2.91	4.44
Two Layers Wet Burlap & One Layer Blue Tarp	6/10/2011	12.98	4.38	2.05
Two Layers Wet Burlap & One Layer Clear Plastic	6/10/2011	6.14	0.13	3.91
Two Layers Dry Burlap	6/10/2011	0.84	2.37	4.34
Six Layers Dry Burlap	6/10/2011	2.90	0.56	0.34
One Layer Burleen	6/10/2011	7.51	1.68	0.63

Upon comparing the temperature gradients to each other groups of curing methods showed similar traits.

The six layer dry burlap method kept the temperature gradients very uniform

The two layer dry burlap and the two layer wet burlap have very similar gradients; however the wet burlap kept the overall sample temperature much cooler than the dry burlap method.

The no cure, single layer curing compound, and misting all showed similar trends in the test. Neither the single layer curing compound nor the misting methods show a significant difference from the no cure method.

The two layers of wet burlap with one layer of blue tarp and the one layer of Burleen methods showed similar gradients. These methods seem to increase early sample temperatures much more than the previously mentioned methods.

The two layers of wet burlap with one layer of clear plastic showed very non uniform temperature gradients as well as large differences between the gradients over time. This method also showed an increase in early sample temperatures.

2.3.5 GUIDANCE

After evaluating the results, the data supports the notion that temperature related curling is controlled more by the curing methods insulation ability rather than whether or not the method utilizes water. However the use of wet burlap also promotes early age hydration in the concrete.

However to have the best control on the temperature gradients one should use multiple layers of dry breathable material, such as burlap, than a wet curing method.

The use of tarps, plastics and other covering methods, like Burleen, is not suggested if temperature related curling is a concern. The application of these methods alone or in combination with other materials, like wet burlap, increases the concrete temperatures and gradients.

There is no noticeable difference of the single layer curing compound, hourly misting, and no curing method. None of these are suggested where temperature related curling is a concern.

2.3.6 OTHER EFFORTS

Larger samples that are 3'x3'x8" have been investigated and the results will be included in the summary report for Phase 1. Work will also be continued in Phase 2 of the project.

Other future efforts in the advancement of this test may possibly include, but are not limited to; the testing of different curing methods, use of a climate controlled chamber during curing, modification to sample design, and/or monitoring a greater spectrum of atmospheric conditions during curing for outside testing.

3.0 DETERMINING REGIONAL INPUTS FOR THE MEPDG

It has been widely published that much more accurate pavement designs can be determined if material input values can be obtained. It is unrealistic to find these values for all of the possible materials in the state of Oklahoma. The following variables were found to be significant and were investigated within this project to determine typical values for the state of Oklahoma.

1. Coefficient of thermal expansion (CTE)
2. Strength
3. Concrete Shrinkage

The results from the strength testing were included in the annual report from year two of the project. This report will contain the CTE and shrinkage data for typical mixture designs from the state of Oklahoma.

3.1 COEFFICIENT OF THERMAL EXPANSION

3.1.1 INTRODUCTION

The coefficient of thermal expansion (CTE) is the amount of strain a materials experiences for a given change in temperature. The CTE is an important parameter when investigating the performance of a concrete pavement as it contributes to the stresses a concrete pavement experiences from environmental temperature changes. These stresses can be a result of warping and curling, a combination of thermal strains combined with traffic loading, and frictional stresses between the pavement and the sub base. (Huang, 2004)

The CTE of a mature concrete depends on the individual CTE of the paste, fine aggregate, coarse aggregate and the volume each one makes up of the mixture. However, the CTE of a mixture is most influenced by the type of coarse aggregate used, as this material typically makes up around 50% of the volume of the mixture.

ODOT has significant interest in finding the CTE values for common concrete pavement mixture designs for the state of Oklahoma. These are important inputs for the Mechanistic Empirical Pavement Design Guide (MEPDG).

A special testing apparatus is described in AASHTO T 336-09 “Standard test method for the coefficient of thermal expansion of hydraulic cement concrete” to investigate the CTE of a concrete specimen. Verification testing completed by the FHWA on two independently purchased devices from Gilson do not produce comparable results from the same specimens. Several visits from Gilson technicians have not lead to an improvement in the equipment. It was also mentioned that there is no way to directly capture the measurements of the CTE device, and only the final results from the analysis are reported to the user. Because of the lack of transparency and repeatability from the machine the FHWA recommended that a device be built for CTE research

3.1.1.1 Background

Several test methods exist for determining the CTE of concrete. Most widely used is AASHTO TP 60-00 (TP 60). The TP 60 was recently modified and re-designated as AASHTO T 336-09 (T 336) when it was discovered that there was an error regarding the calibration of the testing equipment. Currently, all state departments of transportation (DOT) use T 336 with the exception of Texas (Tanesi, et al. 2010).

3.1.1.2 TP 336

The measurement of CTE with TP 336 is achieved by measuring the length change of a saturated concrete specimen as it is subjected to different temperatures. The temperatures required by the method are obtained by using a water bath with a pump to cycle water in the chamber. Deformation of the frame is accounted for by measuring a steel specimen of known CTE in the apparatus. A correction factor is then determined to account for the frame deformation (American Association of State Highway and Transportation Officials 2009).

3.1.1.3 Prior Issues Encountered With TP 336

Researchers at Auburn University encountered issues with determining the CTE of the same concrete specimens at the same temperatures with different linear variable differential transformers (LVDT) even though the LVDTs were of the same make and model. The Auburn researchers hypothesized that these different CTE values were caused by heat transfer through the components of the testing frame and LVDT. (Sakya-Bekoe 2008)

Several proposed modifications were made to minimize these effects. These modifications include:

- A machined ceramic collar (high temperature glass-mica stock) to isolate the LVDT from the cross bar.
- A machined ceramic spacer (high temperature glass-mica stock) to isolate the tip of the LVDT from the water.
- A machined Invar cylinder to isolate the ceramic spacer from concrete specimen and water.

These three components are listed in figure 49.

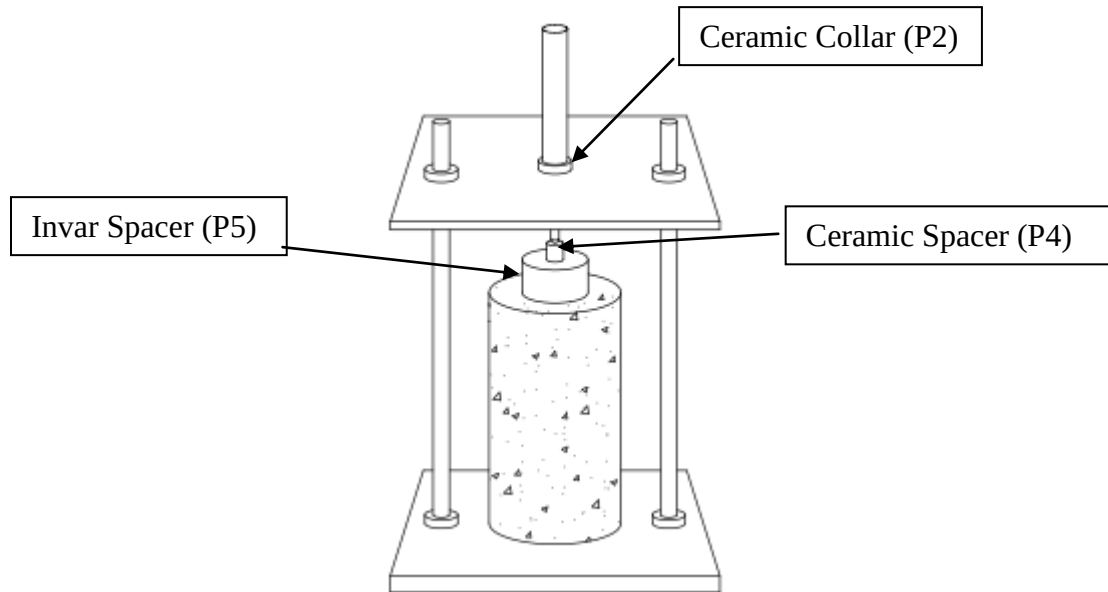


Figure 49: Assembled CTE Frame And Sample With Labels

The “P” designations found in the labels of figure 49, and various other locations in this chapter, represent the component numbering assigned to each individual part of the testing apparatus. These designators are meant to help relate the images to one another as well as associate them with the overall apparatus.

3.1.1.4 The Current Test Method

In addition to these changes the researchers at OSU felt it was important to have a test setup that was able to continuously measure the length change of the sample. This is not currently required in the test method.

Currently, in TP 336, a sample is cooled to $50^{\circ}\text{F} \pm 2^{\circ}\text{F}$ for a period of time long enough to reach thermal equilibrium in the sample. The measured LVDT length is then recorded and the sample is heated to $122^{\circ}\text{F} \pm 2^{\circ}\text{F}$ until it is at equilibrium and the length is again recorded with the LVDT.

3.1.2 APPARATUS

This section details the specific apparatus constructed to evaluate the CTE of concrete cylinders.

3.1.2.1 Rigid Support Frame

Figure 50 shows an exploded assembly diagram of the apparatus used to evaluate CTE.

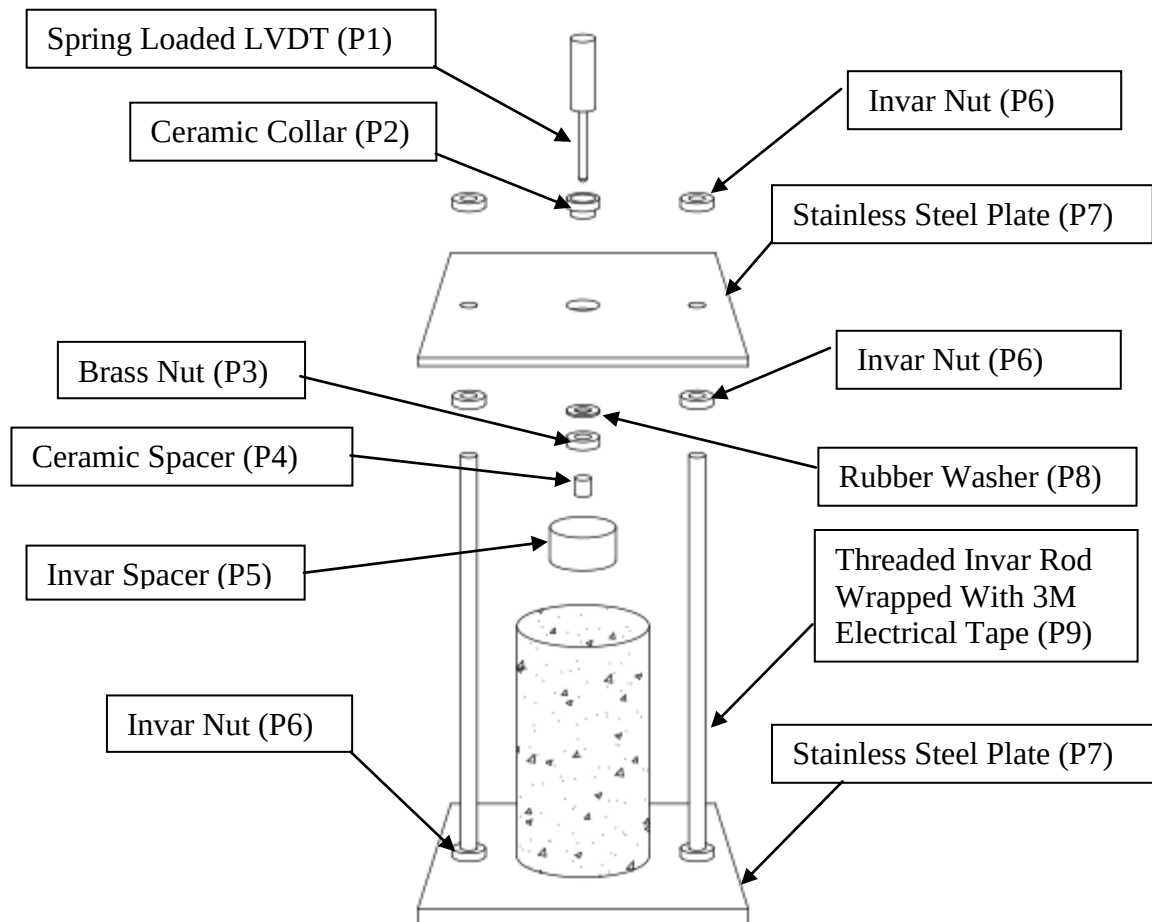


Figure 50: Exploded Assembly Of CTE Frame And Sample With Labels

3.1.2.1.1 Frame

The rigid support frame was constructed in accordance with Appendix X.1 of TP 336. The top and bottom plate are stainless steel, while the vertical support rods are machined from Invar. The rods are wrapped with tape for protection against corrosion the full length between the two stainless steel plates. Three semi-spherical support buttons are equally spaced along a 2" diameter about the bottom plate. Figure 51 shows one of the frames prior to placement of an LVDT.

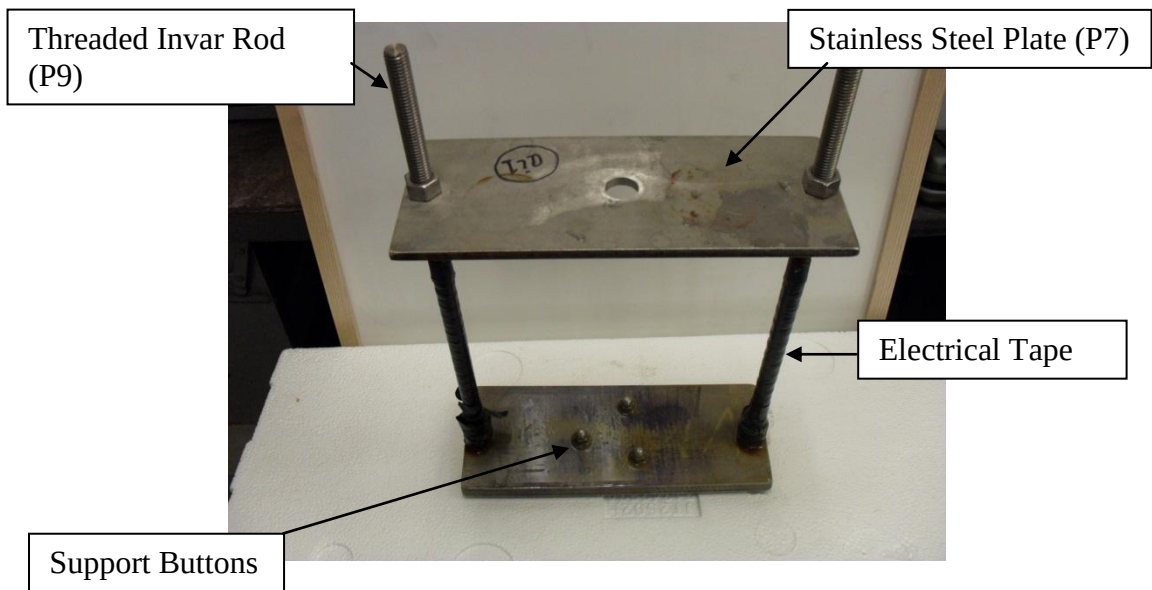


Figure 51: Assembled Rigid Frame With Labels

3.1.2.1.2 Ceramic Collar

A ceramic collar was used to insulate the LVDT from the top plate of the frame. The collar was threaded to mate with the LVDT. It seats the LVDT in place on the plate with a metal nut and rubber washer and is threaded to match the LVDT. Figure 52 shows one of the ceramic collars constructed by OSU.



Figure 52: Ceramic Collar (P2) Suggested By Auburn University

3.1.2.1.3 Ceramic Spacer

A ceramic spacer was machined and positioned concentrically on top of the Invar spacer supporting the piston head of the LVDT. This ceramic spacer is thought to insulate the LVDT from the radiant heat from the water.

3.1.2.1.4 Invar Spacer

An Invar spacer was machined and positioned concentrically with the concrete cylinder. The Invar is used to separate the LVDT from the surface of the sample and serves as a visible measure of water level within the holding tank. Both the ceramic spacer (P4) and the invar spacer (P5) are marked along their radius to aid in alignment. These can be seen in figure 53.

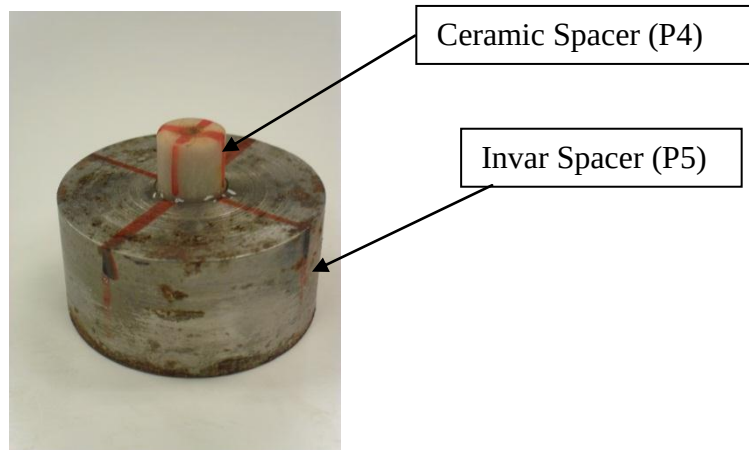


Figure 53: Ceramic Spacer (P4) Aligned On Top Of Invar Spacer (P5)

3.1.2.2 Water Bath

This section details the components used for the water bath.

3.1.2.2.1 Circulator

A VWR Signature Heated/Refrigerated water circulator was used for maintaining the desired water temperature within the holding tank. It has a readout accuracy and temperature stability of $\pm 0.25^{\circ}\text{C}$ and $\pm 0.1^{\circ}\text{C}$ respectively. The circulator has internal storage large enough to contain a single frame & LVDT assembly. The external holding tank was used by OSU so that two samples could be evaluated at once. The circulator can be seen in figure 54.



Figure 54: VWR Water Circulator

3.1.2.2.2 Vibration Damper

A concrete block was cast in-line with the water out line from the circulator before the holding tank. This mass of concrete reduces vibrations in the water from the circulator before they reach the holding tank. The concrete block was cast around the outlet line between the circulator and the holding tank. Figure 55 shows the vibration damper.



Figure 55: Concrete Vibration Damper

3.1.2.2.3 Holding Tank

The holding tank is made from a 10 gallon cooler. The lid has been replaced with a removal wood cover which has a viewing window and openings for the LVDT wiring. The sides of the cooler were tapped to accommodate an inlet and outlet hose for water circulation.

The lid of the holding tank consists of a removable wood frame with a clear plastic viewing window. A rectangular hole was cut in the viewing window to allow the LVDT and wiring to pass through while still providing some insulation to the holding tank. The markings seen in figure 56 are representative of the individual frame and LVDT assemblies. Figure 56 shows the lid of the holding tank. Figure 57 shows the complete CTE assembly and is labeled.



Figure 56: Holding Tank Lid

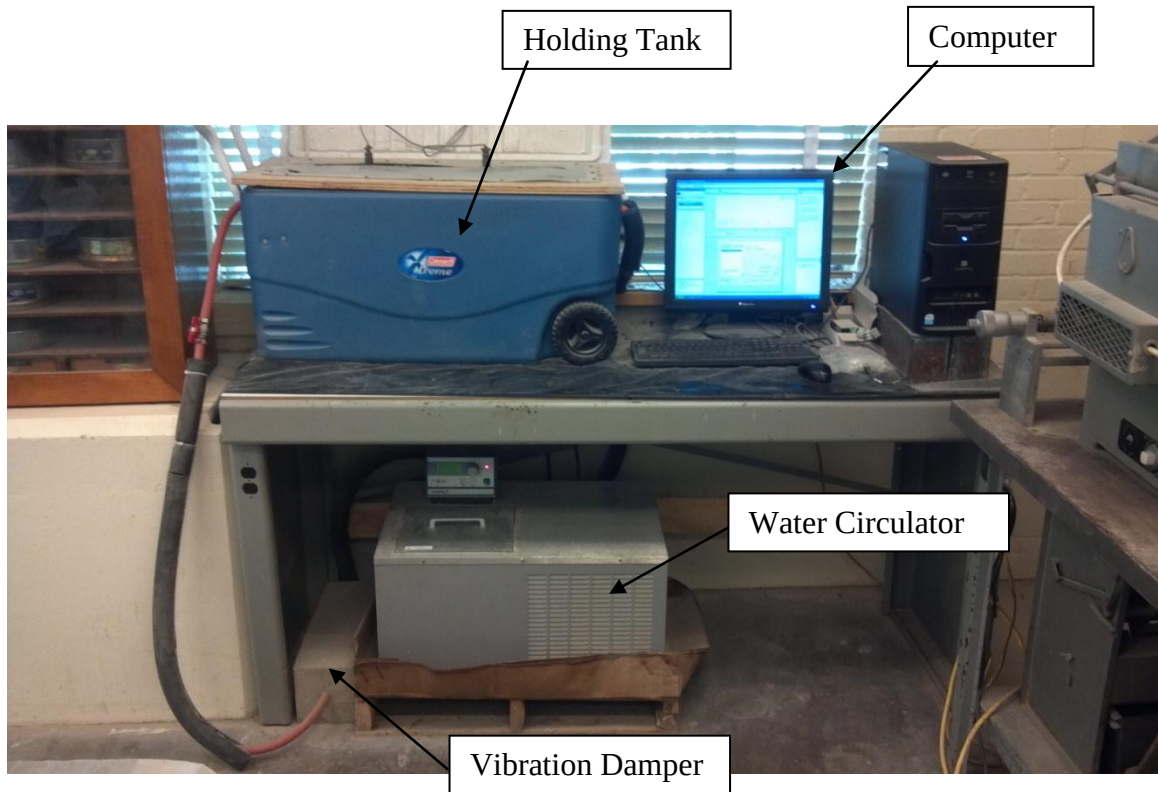


Figure 57: Complete CTE Apparatus With Labels

3.1.2.3 Linear Variable Differential Transformer

The GCD-121-125 Schaevitz gage head LVDT. These are DC LVDTs and are of the spring loaded category. This LVDT is widely used by the FHWA, Auburn University, and the University of Texas. Figure 58 shows an image of the gage head LVDT.



Figure 58: Schaevitz LVDT

3.1.2.3.2 Signal Carrier

A National Instruments NI USB 9162 C series USB signal carrier was used to connect the LVDT's to the computer software. This was chosen as it allowed a continuous measurement to be taken for both of the LVDTs. The signal carrier allows communication from the LVDT to the computer software. Figure 59 shows the USB carrier used in this experiment.



Figure 59: National Instruments USB Signal Carrier

3.1.2.3.3 LabVIEW Software

The software package used to gather and record the voltage data from the LVDTs was LabVIEW 2009. The software allowed output of the voltages into Microsoft Excel spreadsheets for further analysis. Excel spreadsheets were developed at OSU to analyze

the signal data from LabVIEW. These spreadsheets make CTE calculations in accordance with TP 336.

3.1.3 METHODOLOGY

3.1.3.1 LVDT Calibration

A rigid frame is used to calibrate the LVDTs individually. A LVDT is first placed in the rigid frame and its gauge head is extended to its full length. The voltage at this length is recorded. Figure 60 shows the calibration of an LVDT.

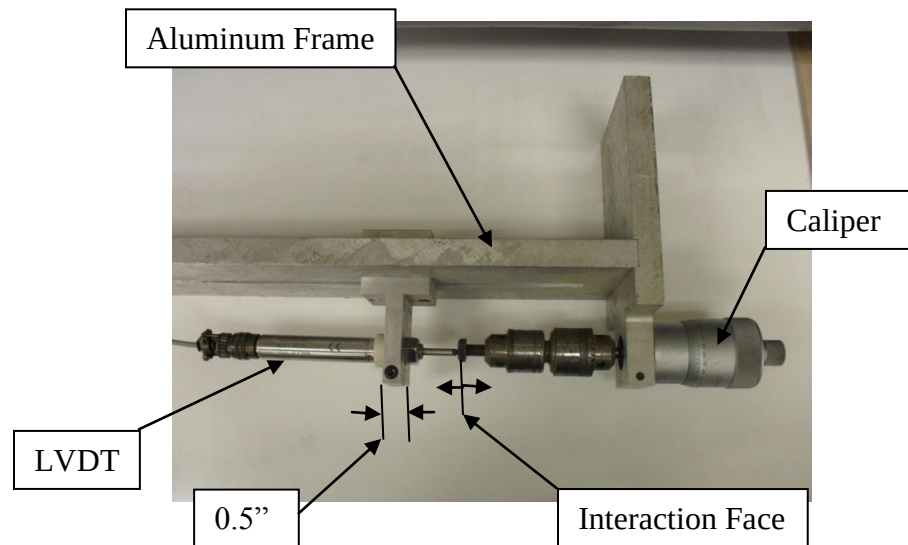


Figure 60: LVDT Calibration Assembly With LVDT In Place

Increasing displacements of 0.025" are imposed on LVDT with a very precise mechanical caliper and their relative voltages recorded. These displacements are made until the gauge head is complete compressed. The data is plotted in a voltage versus displacement graph, and the calibration equations are derived based on the slopes of these lines. Literature suggests that calibration should be done every six months. (Tanesi, et al. 2010)

Figure 61 shows the results of a successful LVDT calibration. The solid line represents actual data recorded while dashed line is the best fit line from which the calibration equation is derived.

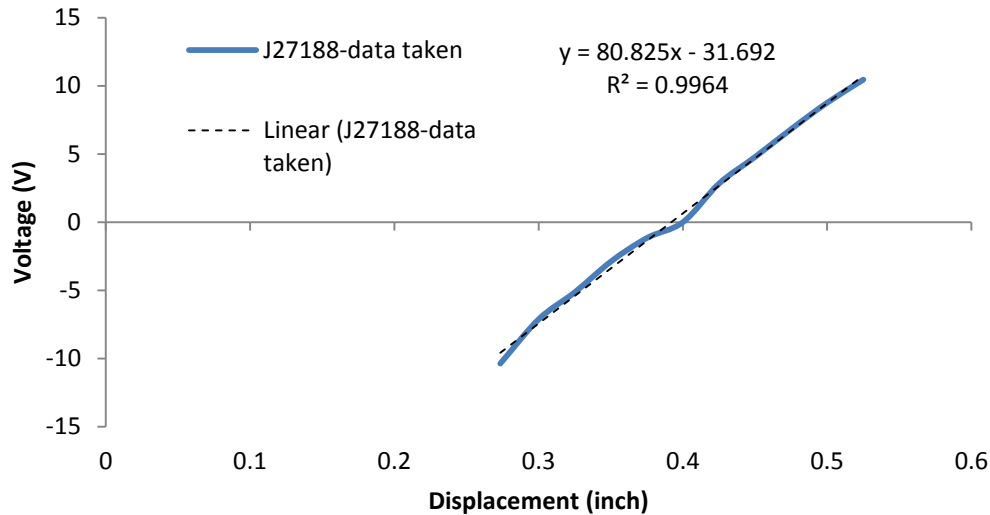


Figure 61: Calibration Results From LVDT J27188

3.1.3.2 Frame Calibration

The correction factor for each rigid frame was found in accordance with TP 336. A third party laboratory was used to evaluate the CTE of a 410 stainless steel calibration specimen. The same specimen was then evaluated by OSU to determine the correction factor for each frame.

The third party laboratory reported the average CTE as $5.8 \pm 0.1 \times 10^{-6} / ^\circ\text{F}$. The specimen was 4" in diameter, 7" in length, and was evaluated in a custom quartz dilatometer in air according to a modified ASTM E228-06. The reported average CTE was calculated as a secant slope of the polynomial regression evaluated at the temperature extremes of 50 and 122°F.

3.1.3.3 Sample Preparation

This section details the steps which take place to prepare the individual samples for testing.

3.1.3.3.1 Sample Size

A premeasured jig was used to cut to concrete specimens to a length of 7.0 ± 0.1 " with a wet saw. Samples used are 4" diameter concrete cylinders. Table 9 shows a standard mix designed used during the CTE sample preparation. All sample mixes were performed on the same volume percentage.

Table 9: Typical CTE Mix Design Used For All Samples

	weight (lb)	volume (%)
cement	451.2	8.5
fly ash	112.8	2.5
water	231.2	13.7
rock	1850	42.3
sand	1244	28.0
air	-	5.0
sum	3889.2	100

3.1.3.3.2 Sample Submersion Period

All samples are submerged in a saturated lime water bath for a period no less than 48 hours and until the incremental weight change when measured in 24 hour intervals is less than 0.5% as per TP 336.

3.1.3.3.3 Sample Marking And Average Length

Samples are marked across their diameter at 45° intervals on the top and bottom faces of the cylinder. A digital caliper is used to take measurements at these intervals around the entire cylinder. These eight measurements are averaged to attain the samples overall average length. Figure 62 shows a sample being measured for average length.



Figure 62: CTE Cylinder During Measurement With Alignment Markings

3.1.3.4 Apparatus Preparation

This section details the steps which take place to prepare the water bath and rigid frame prior to sample placement.

3.1.3.4.1 Water Bath Temperature

The water bath temperature is at room temperature at the time when the samples are placed in the reservoir. After sample placement, data recording is begun and the initial ramp temperature is set to 50°F. Samples are evaluated for an interval of 24 hours at which time data is collected and a new ramp at 122°F is begun. The same recording interval is maintained. Two more intervals follow for each sample resulting in two 50°F and two 122°F intervals per sample.

TP 336 currently requires that the samples are heated/cooled until thermal equilibrium is reached. This equilibrium is described as the condition when consistent readings of the LVDT are recorded to the nearest 0.00001 inch at 10 minute intervals over a half hour period. OSU takes length measurements every 150 seconds over a 24 hour period. This period and interval combination was chosen to better insure that strain equilibrium within the sample was reached every time.

Figure 65 shows the relation to the deflection readings from a LVDT to the temperature intervals. Notice that it takes multiple hours for the sample to reach equilibrium. This trend is the reason why OSU evaluates each temperature interval for 24 hours to ensure equilibrium.

Since the interference does require filtering of the data, it was important to OSU researchers to record more than enough data to provide accurate CTE results with every trial after the filtering took place.

3.1.3.5 Sample Placement

Samples are placed concentrically with the center of the LVDT and the three support buttons on the bottom plate of the rigid frame. On top of the sample are the Invar and ceramic spacers. Alignment markers placed along the diameters of both spacers and the sample allow for proper alignment. Figure 63 shows the alignment of the components and a sample.

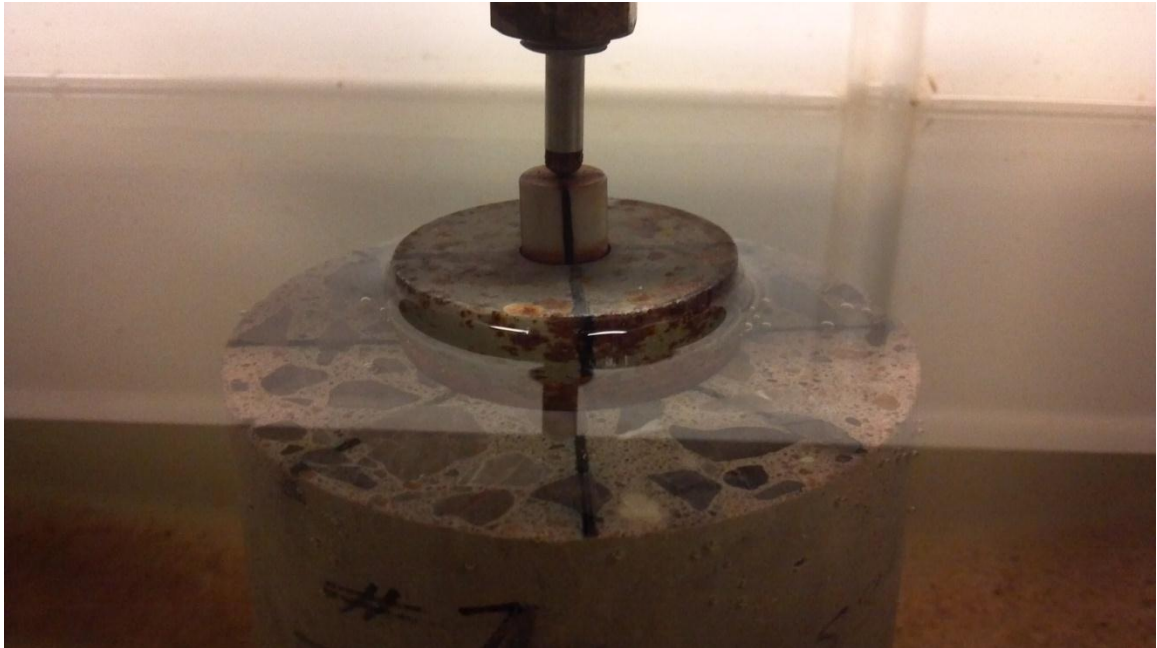


Figure 63: Aligned LVDT, Ceramic Spacer, Invar Spacer And Sample In The Holding Tank

3.1.3.6 Software Execution

The LabVIEW software begins recording LVDT voltages at 150 second intervals once the samples have been properly placed and the water bath program had been initiated. After the 24 hour recording period is reached, voltage data is exported to Microsoft Excel. This is the procedure for a single ramp and is repeated three times for all of the samples investigated.

3.1.3.7 Data Analysis

Once data has been collected from LabVIEW, the voltages are converted into deflections with the conversion formulas previously derived for each LVDT. These deflections are then entered in to Microsoft excel for analysis as per TP 336.

Any noise interference is filtered out of the data by using the filter function imbedded in excel. This unknown interference is seen on every set of data and has been seen previously by other researchers that have used the same equipment for the same test (Won 2006).

To filter the data, the deflection readings prior to equilibrium should be removed as well as the majority of the visible interference. This provides a rough data set which is a good representation of the actual deflection readings and is followed by a second filtering procedure to further refine the data. Figures 64 and 65 show deflection data before and after the first filtering process respectively.

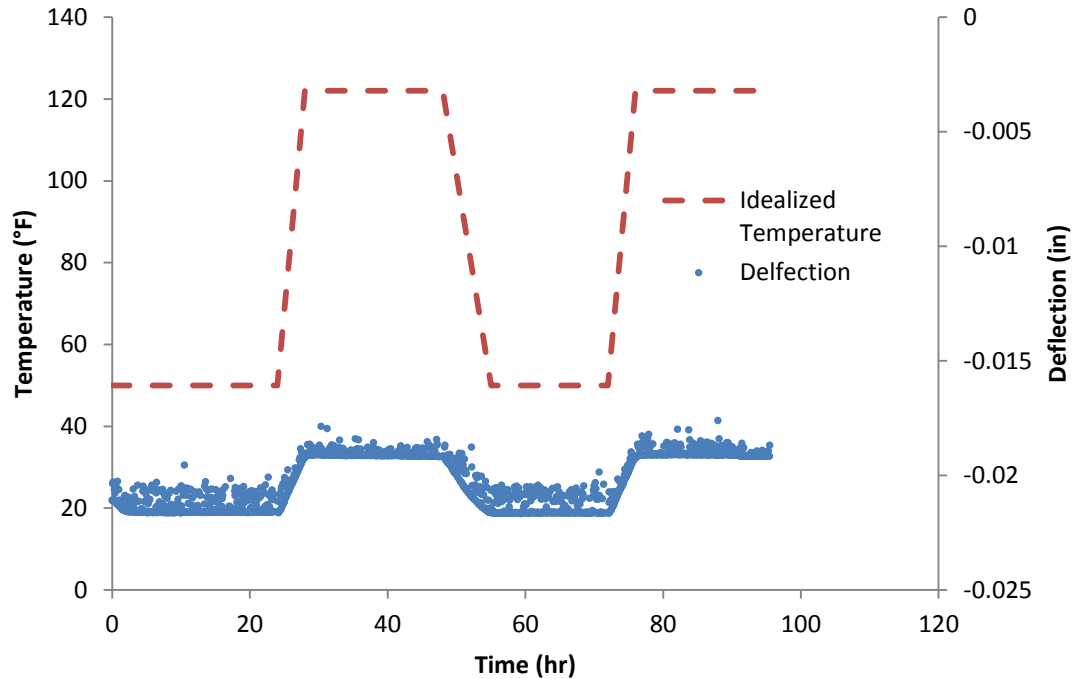


Figure 64: Deflection Data Prior To The First Filtering Process

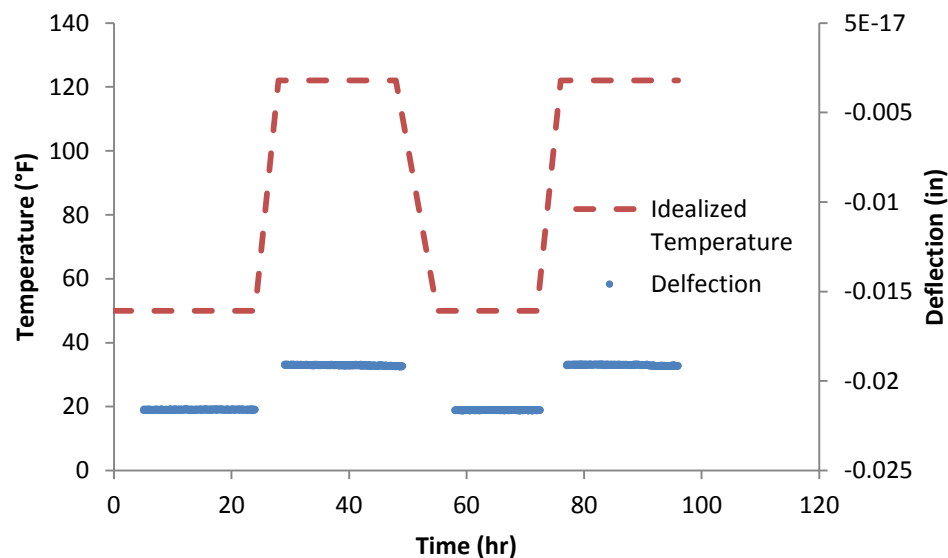


Figure 65: Deflection Data After The First Filtering Process

After the data has been filtered the first time, a second filtering process is imposed on the data. This filter consists of taking the difference between each data point. Only data points showing a difference of 0.00002 inches are kept for further use. This is done to ensure that the deflections used for CTE evaluation are as similar as possible further eliminating the possibility of interference being present in CTE evaluation.

After the second filtering process, the deflections are averaged to attain representative sample lengths at each temperature extreme. Each sample undergoes 4 temperature extremes which make up 3 temperature ramps as previously described. The average lengths determined at each temperature extreme are then used to calculate the length change the sample undergoes during each ramp.

The need for filtering may not have been experienced in previous CTE testing methods since intervals of 150 seconds were not used for continuous monitoring. With the mentioned filtering procedures, OSU has high confidence in its results and the accuracy of the results can be seen in the low coefficients of variance for each trial.

The three ramps are used to calculate three CTE values, as per TP 336, for each sample. This is done to ensure that average CTE value is accurate and has a low coefficient of variance.

3.1.4 RESULTS

Table 10 is comprised of all samples evaluated and their average CTE values. The table also includes other relevant information about the aggregates used in each sample. Notice the extremely low coefficients of variance.

Table 10: CTE Testing Results And Sample Information For All Samples Tested

Sample	Mineralogy	Abs. (%)	SG (SSD)	Dry Rodded Unit Weight (lb/ft ³)	Avg CTE (10 ⁻⁶ /°F)	Frame	CTE (10 ⁻⁶ /°F)	Diff. between frames (10 ⁻⁶ /°F)	Std. Dev. (10 ⁻⁶ /°F)	COV (%)
Coleman	Dolomitic Limestone	0.55	2.77	173.1	5.3	0	5.2	0.2	0.044	0.85
						1	5.4		0.034	0.62
Cooperton	Dolomitic Limestone	0.92	2.81	147	5.2	0	5.2	0.1	0.028	0.54
						1	5.1		0.11	2.17
Davis	Rhyolite	0.64	2.71	165.6	5.5	0	5.2	0.6	0.062	1.19
						1	5.8		0.17	2.85
Drumwright	Limestone	0.52	2.71	168	5.6	0	5.39	0.3	0.017	0.32
						1	5.71		0.16	2.78
Hartshorn	Limestone	1.13	2.62	169.2	4.5	0	4.5	0.0	0.054	1.20
						1	4.5		0.098	2.18
N. Troy	Limestone	1.45	2.71	171	5.6	0	5.5	0.2	0.019	0.34
						1	5.7		0.12	2.13
OKAY	Limy Sandstone	3.06	2.51	155.1	5.5	0	5.3	0.4	0.25	4.75
						1	5.7		0.082	1.44
Sawyer	Sandstone	2.02	2.52	156.1	6.8	0	6.9	0.3	0.23	3.40
						1	6.6		0.12	1.84
Richard Spurr (5.5 Sack)	Limestone	0.89	2.67	168.1	5.0	0	4.7	0.5	0.021	0.44
						1	5.2		0.054	1.04
Richard Spurr	Limestone	0.89	2.67	168.1	5.1	0	4.9	0.4	0.017	0.35
						1	5.3		0.051	0.96
Richard Spurr (6.5 Sack)	Limestone	0.89	2.67	168.1	5.1	0	4.9	0.3	0.034	0.70
						1	5.2		0.035	0.67

Also, note that there is not a noticeable CTE difference between the three Richard Spur samples. These three samples vary in paste content and their results suggest that the CTE value is not dependent on paste content, but is dependent on the aggregate type in the sample.

3.1.5 DISCUSSION

When comparing the average CTE values in Figure 66 it can be seen that the majority of the samples are between 5 and $5.5 \times 10^{-6}/^{\circ}\text{F}$. Removing the two outliers (Hartshorn and Sawyer), the average CTE value is $5.4 \times 10^{-6}/^{\circ}\text{F}$. This value is representative of all aggregates except Sawyer, a sandstone, which has a higher Average CTE of $6.8 \times 10^{-6}/^{\circ}\text{F}$. Hartshorn is a limestone which showed a low average CTE of $4.5 \times 10^{-6}/^{\circ}\text{F}$. Figure 66 shows all CTE values plotted against each other and the average representative CTE. The samples are ordered in relation to this graph on Table 10.

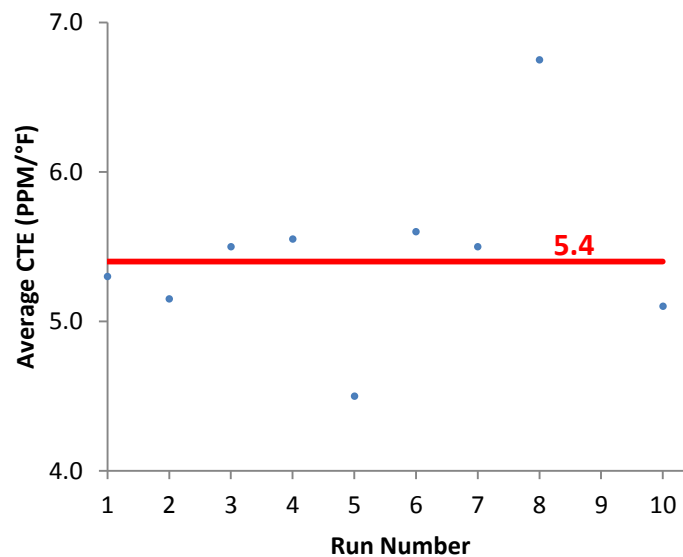


Figure 66: Individual Average CTE Comparison Of All Samples With Overall Average CTE Value

3.1.5.1 Geometry Change

Random changes in LVDT readings were seen in some samples during the testing. These changes can be seen in the figure 67 below as non-typical areas.

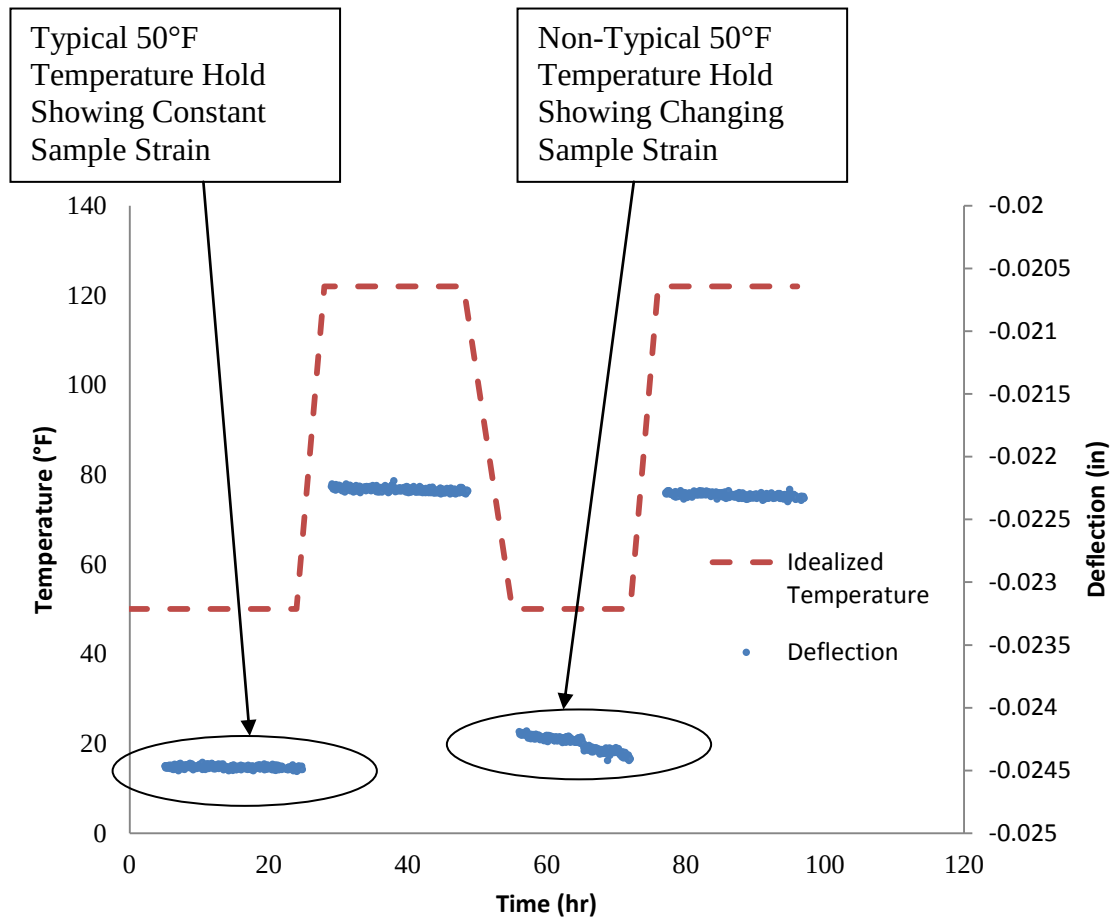


Figure 67: Filtered Non-Constant Geometry

The witnessed change comes in the form of a non-uniform strain pattern where one should be present. It is believed that this is due to the LVDT device. When non-typical deflection data were encountered, the sample was re-tested until typical data was collected for the entire dataset. This was done to ensure that the data was not tainted in any way by suspected LVDT errors. These non-typical changes happened at random so it was important to check the unfiltered datasets before CTE evaluation for non-typical data for every sample. ***This observation would not have been made if the LVDT was not continuously measured.***

These errors were encountered on 8 of the 11 investigated samples and so were frequent.

3.1.6 RECOMMENDATIONS

Commercial CTE testing methods have been shown by others to not be repeatable. The modified version of the CTE test method developed at Auburn with modifications by OSU showed consistent and repeatable results. This is proven by the low coefficient of variation values.

It appears that the modifications to the apparatus made to isolate the LVDT from varying temperatures was helpful and should be incorporated into future versions of this test.

Measurement intervals at 150 second periods over multiple 24 hour intervals at varying temperatures should be strongly considered in future testing. This ensures that errors in testing are not made and that true sample equilibrium is reached for accurate CTE evaluation.

Filtering of the deflection data prior to CTE evaluation is greatly needed to ensure accurate evaluation of the sample. The interference seen during the continuous monitoring of the samples can greatly influence the calculated CTE of any given sample if it is not removed.

The use of multiple frames is also suggested. Testing samples in different frames and comparing CTE values between the two also help minimize errors.

Random changes in length recorded by the LVDT have been noticed during this testing. The source of these changes is unknown and would not have been observed if continuous measurement was not used. These errors occurred frequently and caused samples to have to be retested.

3.1.6.1 Recommended CTE Values For MEPDG Implementation For Oklahoma

One useful finding from the work is that the majority of the CTE values were similar in value. As shown in Table 10 of the nine different aggregates investigated, seven of them were between $4 \times 10^{-6}/^{\circ}\text{F}$ and $5.45 \times 10^{-6}/^{\circ}\text{F}$. This means that ODOT could use $5.4 \times 10^{-6}/^{\circ}\text{F}$ as an input value for the MEPDG for future analysis and provide a reasonable value for all of the aggregates except for Hartshorne and Sawyer. Care needs to be taken to ensure that the version of the software is formatted to receive data from the recently updated version of the PT 336 test. If the version is not the latest, then a correction factor should be used to change the data to the old testing scale.

3.2 DRYING SHRINKAGE OF CONCRETE MIXTURES

3.2.1 INTRODUCTION

A task in this project was to provide the necessary shrinkage input parameters for the MEPDG. The input parameters include: ultimate shrinkage, reversible shrinkage and time to develop 50% of the maximum shrinkage. Laboratory tests that use AASHTO T160 “Standard Method of Test for Length Change of Hardened Hydraulic Cement Mortar and Concrete” with modifications suggested by the MEPDG design manual were used (ARA, 2004). These modifications include using a drying environment of 40% relative humidity instead of 50%. As part of this work the ultimate maximum shrinkage and time to develop 50% of the maximum shrinkage was measured. For reversible shrinkage the assumptions within the MEPDG are recommended.

The paste (cementitious and water) in a concrete mixture is responsible for the volume change when dried. Because of the importance of the paste in the mixture several different paste mixtures were investigated to determine the impact on the ultimate shrinkage. The mixtures were very representative of common concrete mixtures in the state of Oklahoma. They had a 0.41 w/cm, 6 sacks of cementitious material, 20% fly ash replacement, and a 60/40 ratio of coarse to fine aggregate. The same coarse and fine aggregate was used for all of the following mixtures. A typical mixture can be found in Table 8. Mixtures were prepared with different cements and fly ashes and work was also done without fly ash and different paste contents (5.5, 6, and 6.5 sacks of total cementitious).

3.2.2 RESULTS

Table 11, 12, and 13 and Figures 68 thru 73 show the results from the drying shrinkage testing. Table 11 and Figures 68 and 69 show the results for mixtures that contain different cements. Table 12 and Figures 70 and 71 show how mixtures with and without fly ash perform and Table 13 and Figures 72 and 73 show how the results of mixtures with different paste contents. Three samples were investigated for each of the reported values. The average and one standard deviation are shown on each of the figures. Because not all of the specimens were cast and measured at the same time, shrinkage and weight loss values in Table 11, 12, and 13 have been interpolated from the data to 290 days of drying for comparison.

Table 11: Drying Shrinkage For Mixtures With Different Cements

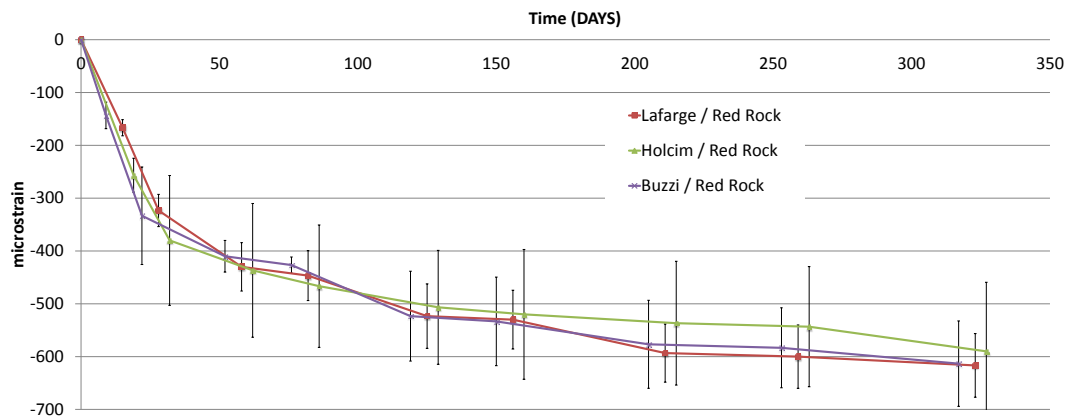
cement	fly ash	w/cm	sacks	ash %	shrinkage (microstrain)	weight loss (%)	Days for 50% of max shrinkage	Slump	Air
LaFarge	Red Rock	0.41	6	20	608	2.86%	25	1.5"	7%
Holcim	Red Rock	0.41	6	20	563	2.61%	28	1"	6.8%
Buzzi	Red Rock	0.41	6	20	601	2.86%	31	1.75"	9%
average					591	2.78%	28		

Table 12: Drying Shrinkage For Mixtures With And Without Fly Ash

cement	fly ash	w/cm	sacks	ash %	shrinkage (microstrain)	weight loss (%)	Days for 50% of max shrinkage	Slump	Air
LaFarge		0.41	6	0	597	2.63%	40	1.5"	6%
LaFarge	Red Rock	0.41	6	20	608	2.86%	28	1.5"	7%
LaFarge	Oklunion	0.41	6	20	656	2.80%	25	1.5"	7%
LaFarge	Muskogee	0.41	6	20	636	2.88%	25	1.75"	7.8%
LaFarge	GRDA	0.41	6	20	620	2.82%	20	1.5"	7%
fly ash average					630	2.84%	25		

Table 13: Drying Shrinkage For Mixtures With Different Paste Contents

cement	fly ash	w/cm	sacks	ash %	shrinkage (microstrain)	weight loss (%)	Days for 50% of max shrinkage	Slump	Air
LaFarge	Red Rock	0.41	5.5	20	530	2.40%	25	0.5"	5%
LaFarge	Red Rock	0.41	6	20	608	2.86%	25	1.5"	7%
LaFarge	Red Rock	0.42	6.4	19	650	3.18%	18	2.5"	9%

**Figure 68: Measured Strain From Drying Shrinkage For Different Cements vs. Time**

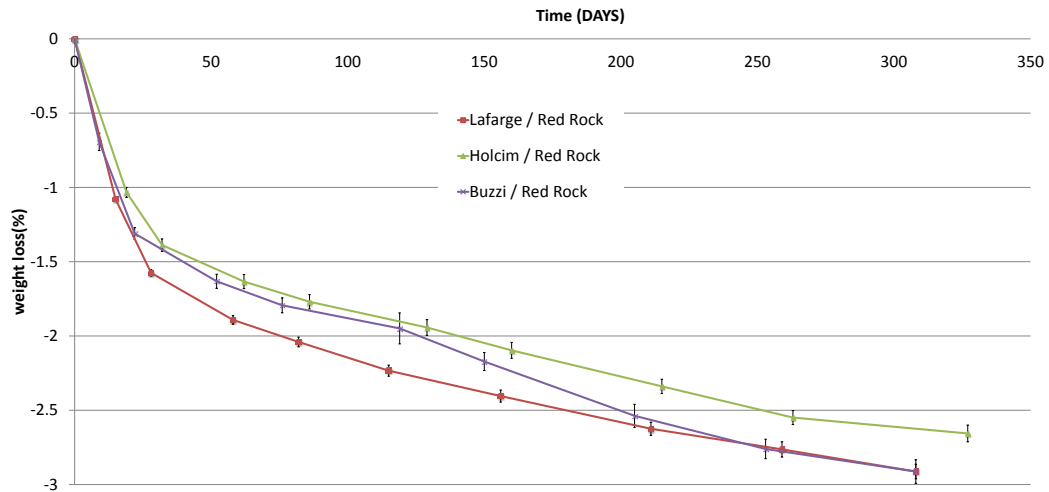


Figure 69: Measured Weight Loss From Drying Shrinkage For Different Cements vs. Time

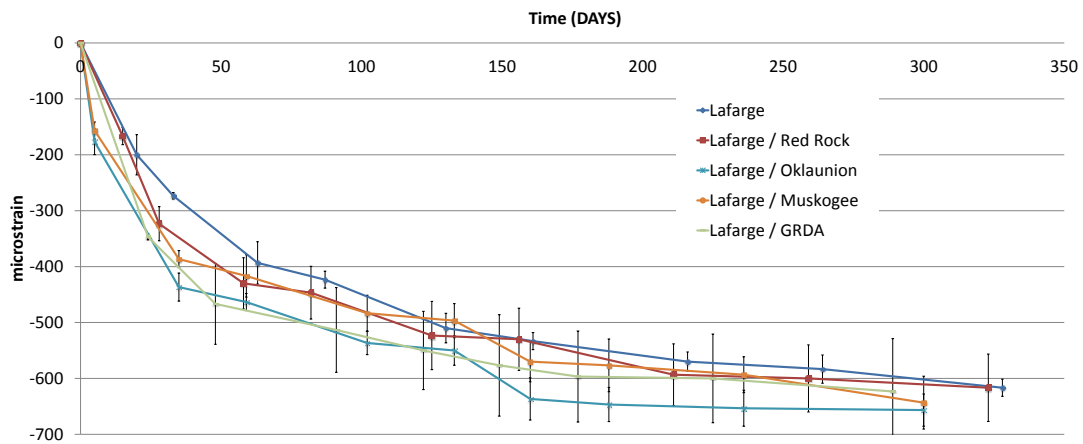


Figure 70: Measured Strain From Drying Shrinkage For Different Types Of Fly Ash vs. Time

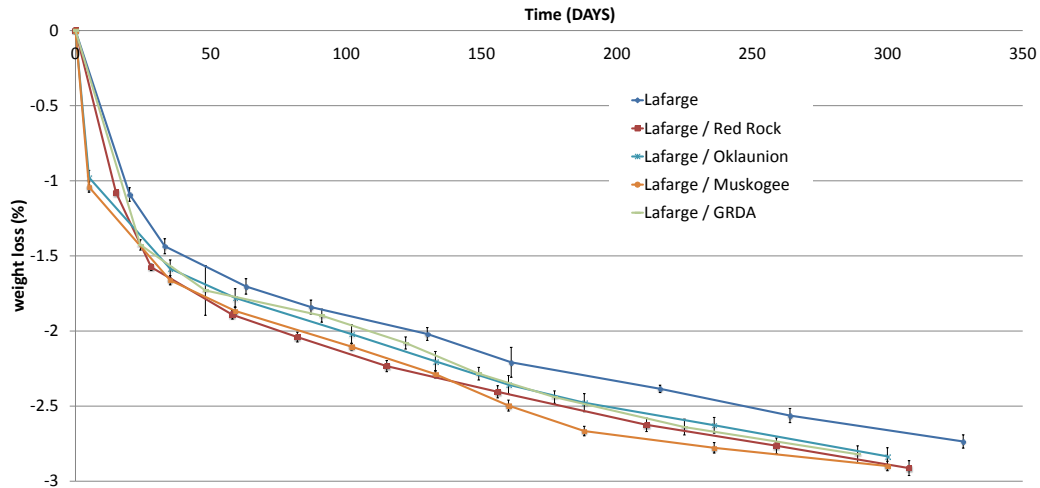


Figure 71: Weight Loss From Drying Shrinkage For Different Types Of Fly Ash vs. Time

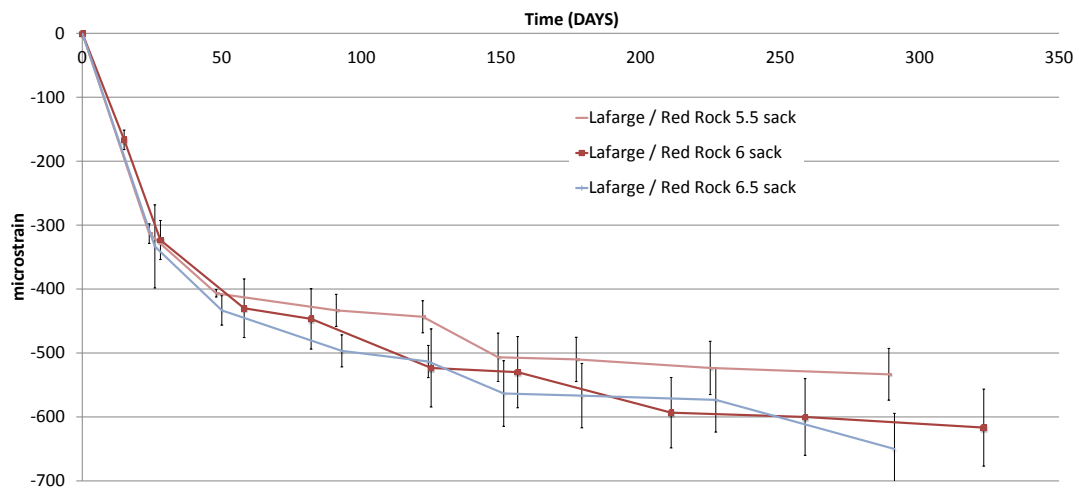


Figure 72: Measured Strain From Drying Shrinkage For Different Paste Contents vs. Time

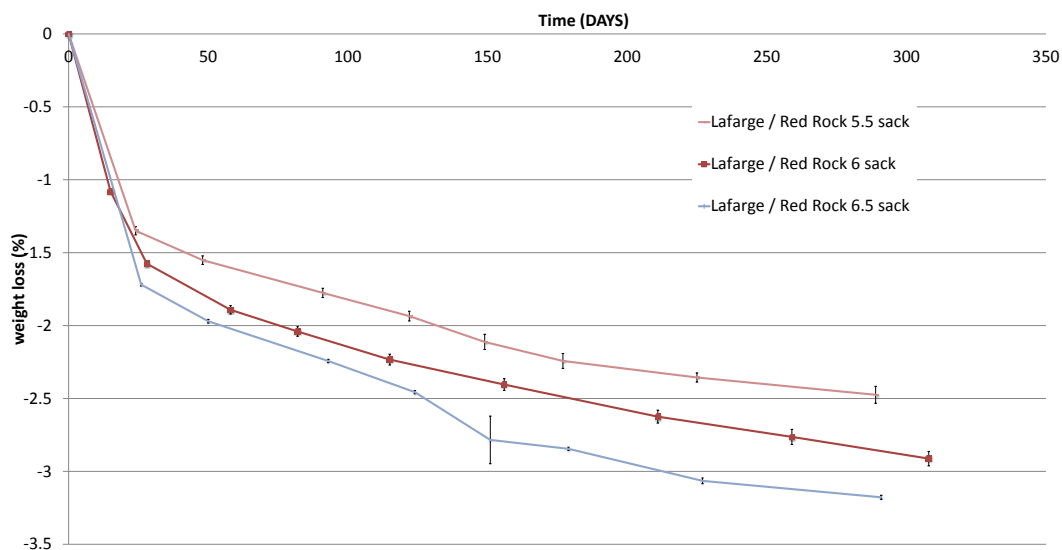


Figure 73: Weight Loss From Drying Shrinkage For Different Paste Contents vs. Time

3.2.3 DISCUSSION

As can be seen in Table 11 there was no significant difference in the observed shrinkage for the three major cements used in Oklahoma for the same mixture. This means that shrinkage of the concrete would not be expected to change based on changes in the cement type.

As shown in Table 12 there is a measurable difference between the mixtures with different fly ashes and without fly ash. Red Rock fly ash was found to have the lowest shrinkage and Oklaunion was found to be the highest. There was a 50 micron difference in the ultimate shrinkage strain between the highest and lowest fly ash investigated. However, there was very little difference in the time required to reach 50% of the ultimate shrinkage. Also, there was an average difference between the fly ash mixtures and the non fly ash mixtures of 33 microstrain. **While differences do exist between concrete mixtures with fly ash it is recommended that an average ultimate shrinkage value of 630 microstrain with 25 days of drying required to reach 50% of the maximum shrinkage.** This is the average ultimate drying shrinkage strain for the mixtures with fly ash. It is very common for fly ash to be used in the state of Oklahoma. This value is a compromise between the measured values and should provide a conservative estimate for the MEPDG inputs.

For the mixtures with a reduced paste content a significantly reduced amount of shrinkage was observed. Of the parameters investigated this had the biggest impact on the ultimate shrinkage performance, as a decrease of paste by 0.5 sack of cementitious showed a decrease in shrinkage of 78 microstrain. For an increase in cementitious of 0.4 sacks there was an increase in shrinkage of 42 microstrain. It is recommended that ODOT encourage a decrease in paste content in the concrete pavement mixtures as this

would promote the long term durability of concrete pavements. The easiest way to obtain this reduction in paste is through the use of optimized graded concrete.

4.0 CONCLUSION

This report has provided a summary of the work completed to date on ODOT project 2208 “Development and Implementation of a Mechanistic and Empirical Pavement Design Guide (MEPDG) for Rigid Pavements”. This document contains completed work for Task D and E. More work is to be completed on Task D during Phase II of this project. In addition funding was provided during Phase I for a field instrumentation of a concrete pavement to verify some of the laboratory findings. This was delayed until Phase II of the project because of issues with receiving the instrumentation in time and communication with the contractor. This work will be completed as part of Phase II of this project and will provide many important insights.

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